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Pacific Outer Continental Shelf

OCS Information Report
MMS 91-0003

# A Summary of the Physical Oceanography of the Pacific Northwest Coast

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U.S. Department of the Interior
Minerals Management Service
Pacific OCS Region

Pacific Outer Continental Shelf

OCS Information Report
MMS 91-0003

# A Summary of the Physical Oceanography of the Pacific Northwest Coast

by David F. Purdy

U.S. Department of the Interior
Minerals Management Service
Pacific OCS Region

1990

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## Abstract

This technical report summarizes current information on the physical oceanography of the Pacific Coast of Washington and Oregon, including information on currents, water mass characteristics, vertical stratification and mixing, upwelling, and waves. A general outline of the California current system is given, including the California and Davidson surface currents, the California and Washington undercurrents, and shelf currents. Conditions affecting local and nearshore currents, considered important in the event of an oil spill, are discussed. A summary of wave data is included from several sources including the Corps of Engineers WIS (Wave Information Study), based on meteorological information, and the Minerals Management Service's Coastal Wave Statistical Data Base (CWSDB), based on high quality data from a system of buoys.

## Acknowledgment

The editorial review and invaluable advice of Martin F. Golden of the Minerals Management Service, Pacific OCS Region, Los Angeles, in the preparation of this report, were very much appreciated.

## INTRODUCTION

The purpose of this report is to summarize available information about the physical oceanography of the coastal and marine waters of Washington and Oregon, with an emphasis on currents, waves, water mass characteristics, and other major features of the region.

Although much remains to be learned, the physical oceanography of the Pacific Northwest has been extensively studied, particularly through the oceanography programs at the University of Washington and Oregon State University. Personnel at these institutions have provided much information for this report, both directly and through their various publications. Many of the documents used were provided by the Oregon State University Sea Grant Program.

Information was also obtained through the National Oceanographic and Atmospheric Administration (NOAA), U.S. Army Corps of Engineers (COE), U.S. Coast Guard (USCG), and the Minerals Management Service (MMS). In addition to literature obtained directly through these agencies, an electronic literature search was conducted through the Minerals Management Service library in the Pacific OCS Region. Relevant publications were obtained from various university libraries in the Los Angeles area as well as directly from the source agencies. With a few exceptions, the literature search for this report was limited to the years 1970 through 1989.

Publications with major sections dealing with the physical oceanography of the Pacific Northwest include the following: Coastal Oceanography of Washington and Oregon (Landry and Hickey, 1989); Coastal Washington - A Synthesis of Information (Strickland and Chasan, 1989); A Summary of Knowledge of the Oregon and Washington Coastal Zone and Offshore Areas (Oceanographic Institute of Washington, 1977); Coastal Upwelling in the California Current System (Huyer, 1983); and The California Current System - Hypotheses and Facts (Hickey, 1979).

Due to the technical nature of this report and the complexity of certain terms used, a list of abbreviations and acronyms, unit conversion table, and a glossary of terms are included in Appendices A, B, and C. The reader is referred to the literature cited or to standard textbooks on oceanography for further clarification.

### Minerals Management Service Responsibilities

The Minerals Management Service, part of the U.S. Department of the Interior, is the agency responsible for administering leases of Federal Outer Continental Shelf (OCS) lands for the development of energy and mineral resources. The 1978 Amendments to the Outer Continental Shelf Lands Act of 1953 assign the role of the Federal Government in managing the development of OCS lands (outside the three mile limit) and protecting the human, marine, and coastal environments of the OCS.

For planning purposes, the OCS of the United States has been divided into planning areas. MMS's Washington-Oregon Planning Area (Figure 1) includes all Federal OCS lands between the seaward extensions of the US-Canadian border and the Oregon-California border.

## CURRENTS

Circulation along the coast of Washington and Oregon follows a complex pattern because of the interaction of permanent ocean currents, local wind driven currents, and currents produced by tide, waves, upwelling, and local topography. "This greatly compounds the difficulty of predictive efforts on the movement of a pollutant, such as oil" (Oceanographic Institute of Washington, 1977).

The deep-ocean currents along the coast of Washington and Oregon are part of the California Current System, an eastern boundary current system. The California Current extends along the west coast of North America from latitudes of about 40° to 50° North (in winter and summer, respectively), where the North Pacific Current (the West Wind Drift) divides into the northerly flowing Alaska Current and the southerly flowing California Current, to southern Baja California, Mexico, where it merges with the westerly flowing Northern Equatorial Current between about 20° and 8° North latitude. The general pattern of Pacific Ocean surface currents is shown in Figure 2 (Pickard and Emery, 1982; Hickey, 1979).

The California Current System consists of the California Current, the Davidson Current, and the California Undercurrent. There is also some evidence of a subsurface Washington Undercurrent. The pattern of current flow along the coast of Washington and Oregon is shown in Figure 3. Major currents in the region are described in the following sections.

### California Current

This surface current is the diffuse, meandering, southward flow along the eastern edge of the North Pacific Gyre (a major clockwise circulation in the North Pacific Ocean). Maximum velocities are in July-August, with typical average velocities on the order of 10 cm/sec (0.3 ft/sec) in summer (Strickland and Chasan, 1989) with the velocity maximum "well seaward of the continental shelf at most locations" (Hickey, 1989). Evidence indicates that the velocity maximum may be at about 250-300 km (155-190 mi) off the coast of Oregon (Hickey, 1979). Width of the California Current is 600-1000 km (375-625 mi) with no well defined western boundary. Maximum depths range from 100-500 m (330-1640 ft) (Wooster and Reid, 1963). Transport has been estimated to be on the order of 10-12 X $10^6$ $m^3$/sec (240-290 X $10^6$ MGD) (Pavlova, 1966).

In spring the southerly flowing California Current moves toward the coast, replacing the northerly flowing Davidson Current. This results in offshore Ekman transport and associated seasonal upwelling of colder, more saline, nutrient-rich water. Upwelling also occurs on an intermittent basis

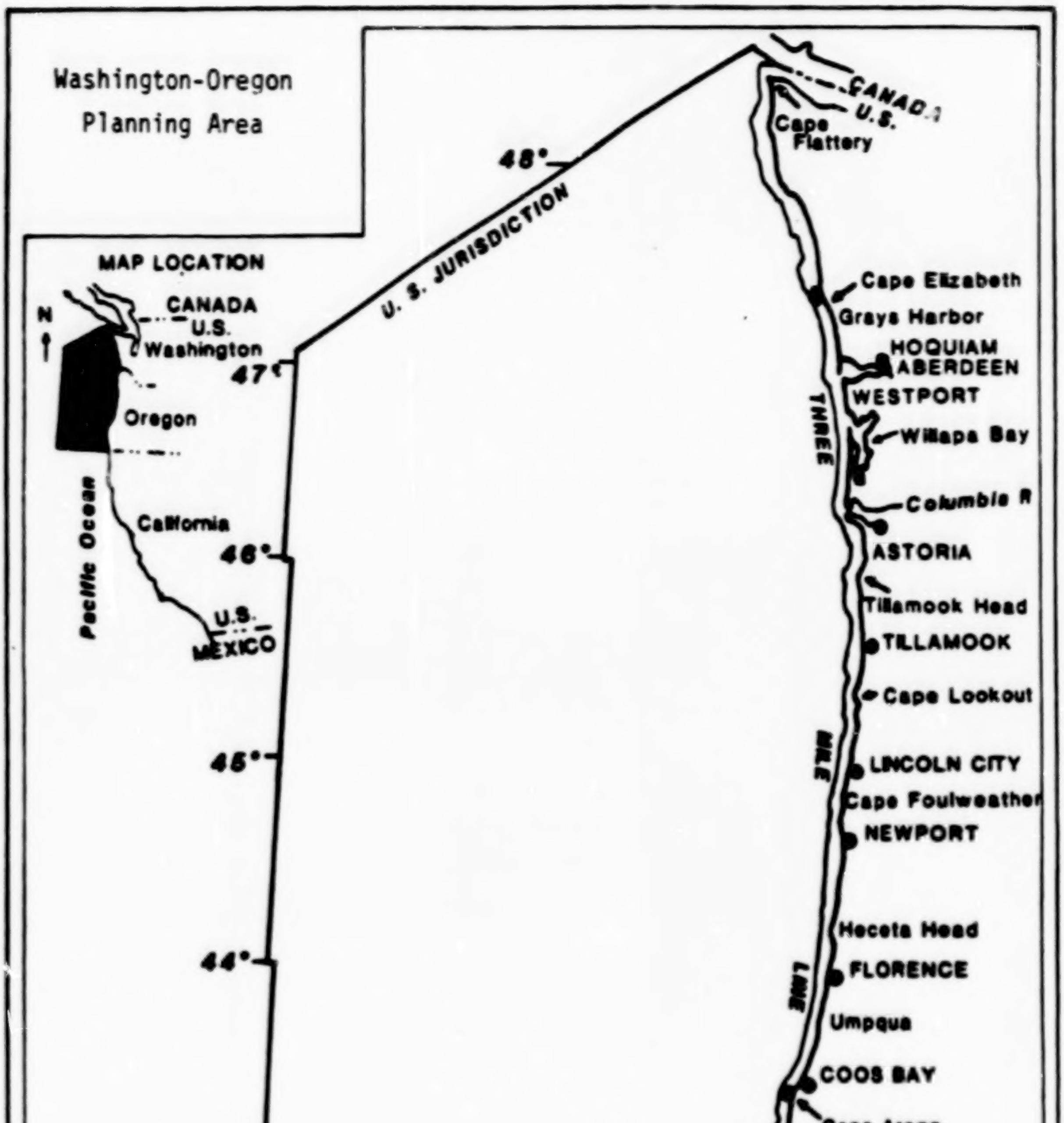

Figure 1. Washington-Oregon Planning Area

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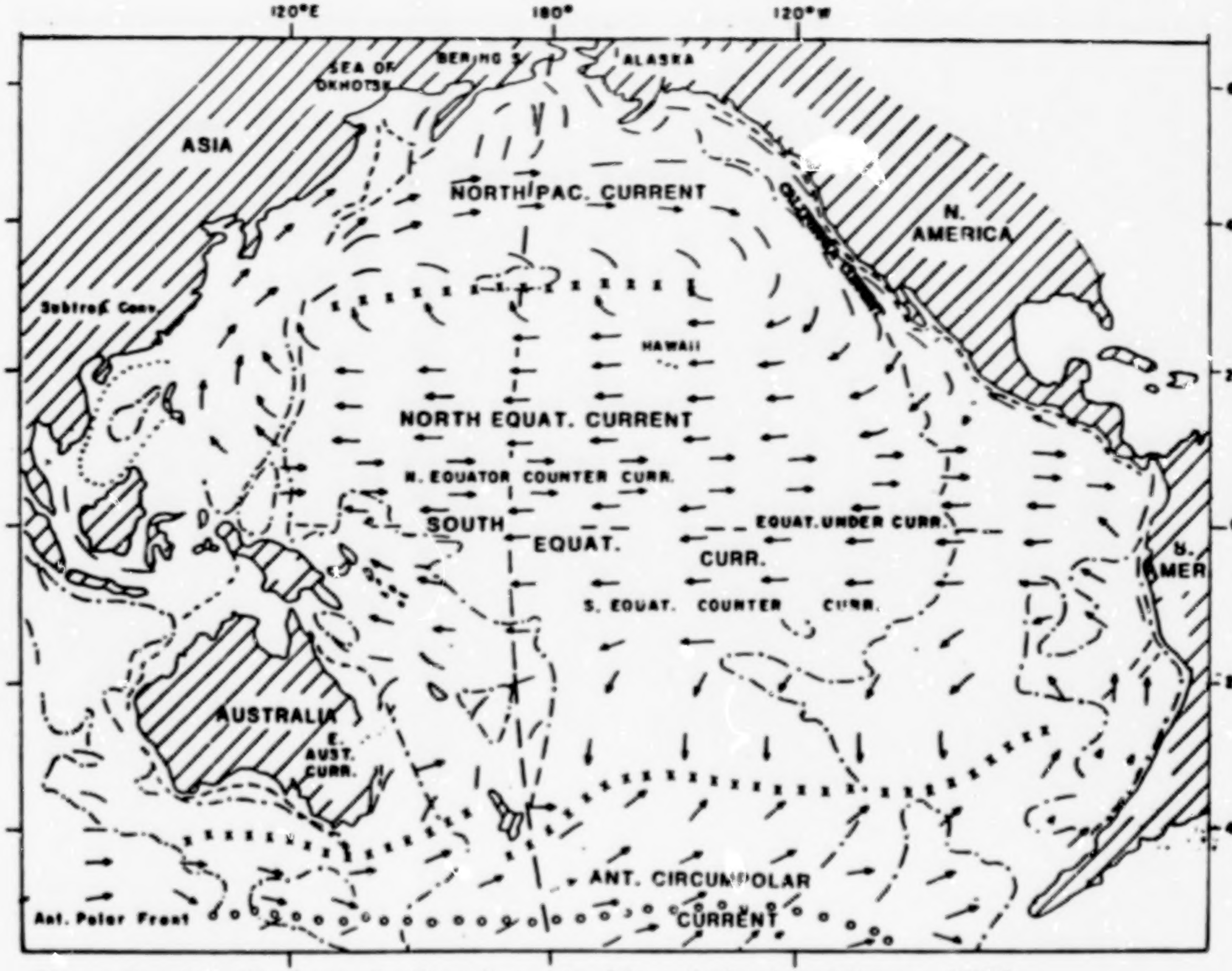

Figure 2. Pacific Ocean Surface Currents (from Pickard and Emery, 1982)

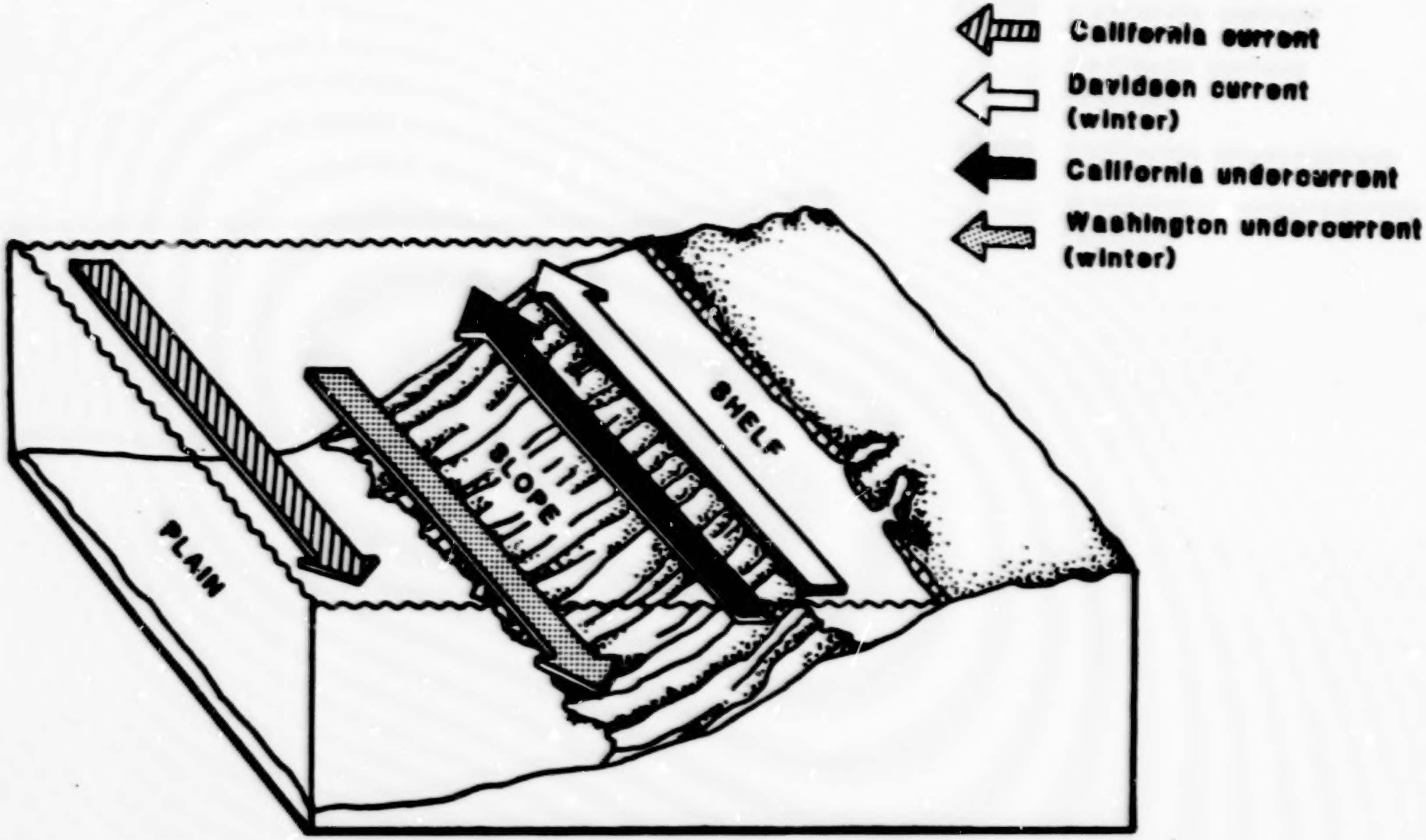

Figure 3. Oceanic and continental slope surface currents (California Current, and Davidson Current in winter) and undercurrents (California Undercurrent, and hypothesized Washington Undercurrent in winter) off Washington (from Strickland and Chasan, 1989, after Hickey, 1989).

in other seasons as well, in the form of short individual upwelling events (Atlas et al., 1977). Ekman transport is the movement of surface water resulting from the balance between frictional force of the wind and the Coriolis force due to the Earth's rotation - resulting in surface water movement to the right of wind direction in the northern hemisphere.

A number of researchers have confirmed the existence of a southward flow during the upwelling season (spring and summer) of a southward coastal jet between 5 and 25 km (3 to 16 miles) off the coast of Oregon. This jet is stronger, narrower, and closer to shore during spring than during summer, averaging 10 km and 15 km (6 and 9 mi), respectively, offshore. Average speed of the jet is about 13 cm/sec (0.43 ft/sec) (Hickey, 1989).

## Davidson Current

The Davidson Current is the northward surface flow inshore of the California Current along the slope and outer shelf (Strickland and Chasan, 1989). In the period from mid-November to mid-February it is the dominant inshore transporter of water and suspended material (Kolitz, 1971).

The Davidson Current begins to develop off the coast of Washington and Oregon in September and becomes well established by January. By spring it begins to diminish and disappears by May. Average speeds of about 20 cm/sec (0.7 ft/sec) are attained (Strickland and Chasan, 1989). Minimum width of the Davidson Current is about 90 km (60 mi) (Oceanographic Institute of Washington, 1977). The Davidson current may be a surface expression of the subsurface California Undercurrent (Pavlova, 1966).

The maximum width of the northward flow near shore along the U.S. Pacific coast increases with latitude. Off California, north of Point Conception, the northward flow is typically within 100 km (62 mi) of the coast. Off Washington and Oregon, northward flow is reported at up to 300 km (190 mi) offshore (Hickey, 1979).

Further offshore, several hundred kilometers off Washington and Oregon, there appears to be a second northward flow separated from the Davidson current by part of the southerly-flowing California Current. This may be contiguous with the broader northerly flowing Alaska Current which is found off Vancouver Island, B.C., Canada (Hickey, 1979).

## California Undercurrent

The subsurface California Undercurrent flows northward along the upper continental slope at a core depth of about 200 m (660 ft). In spring and fall the velocities average about 10 cm/sec (0.3 mi/hr). The current is stronger in summer and winter. Width is on the order of 20 km (12 mi) (Strickland and Chasan, 1989).

Measurements off the southern edge of the Washington coast in July and August indicate that the core of the California Undercurrent was centered about 60 km (38 mi) offshore above the upper continental slope at a depth of about 200 m (650 ft). During late fall and winter the core rises and may be expressed at the surface as the Davidson Current (Hickey, 1979).

### Washington Undercurrent

"There is also evidence that a deeper (400 m/1,300 ft) southward current ... forms during the winter" (Strickland and Chasan, 1989). Both data and modeling results indicate that this current sometimes occurs along the Washington and Oregon slopes in winter. Horizontal characteristics of the current are not known (Hickey, 1989).

### Shelf Currents

"Currents over the Washington shelf tend to follow the seasonal pattern of the oceanic currents, but also are strongly influenced by local winds, bottom and shoreline configuration, and freshwater input. ... On the average, water flows southward in the upper 100 m (330 ft) during summer and northward below that depth. Water over the shelf flows generally northward at all depths during winter; near shore under the Columbia River plume, southward flow may be found" (Strickland and Chasan, 1989).

Surface drift bottle data suggest that the surface movement within 265 km (166 mi) of the Oregon coast is southward from May to August, northward from October to February, and variable in March, April, and September (Hickey, 1979).

The mean summer speed of the surface currents over the Washington shelf, to 20-30 m (60-100 ft) depth, is about 17-20 cm/sec (0.56-0.66 ft/sec) southward and 2-4 cm/sec (0.07-0.13 ft/sec) offshore. Mean winter speed is about 10 cm/sec (0.3 ft/sec) northward. Shelf currents in the bottom layer have a mean velocity of 1-2 cm/sec (0.03-0.06 ft/sec) northward during all seasons. The northward flowing shelf currents have a slight onshore velocity component in most areas (Strickland and Chasan, 1989).

Oscillation periods of variable surface shelf currents in the Pacific Northwest are associated with diurnal tides, semi-diurnal tides, and inertial oscillations, with periods of 25, 12.4, and 17.4 hours, respectively, in the region. Inertial currents are associated with differences in sea surface height such as those caused by rapid changes in wind stress (Huyer and Smith, 1977). Inertial currents are typically 15 cm/sec (0.50 ft/sec) over the shelf and 10-40 cm/sec (0.3-1.3 ft/sec) in the upper 200-300 m (650-980 ft) over the slope (Strickland and Chasan, 1989).

### Tidal Currents

Tidal currents on the shelf typically exceed 10 cm/sec (0.3 ft/sec). These currents tend to flow in an elliptical rotary pattern with the major axis in a northeast-southwest direction. Flow is generally northeasterly on the flood tide and southwesterly on the ebb tide. Near shore these currents are strongly influenced by bottom topography and the flow into and out of estuaries, where the tidal currents may be much stronger than the average wind driven currents (Strickland and Chasan, 1989).

Bourke et al. (1971) report tidal current information from three lightships which operated off the Pacific coast. Two of these were off the Pacific Northwest: The Columbia River lightships operated from 1892 to 1979, off the mouth of the Columbia River, at Lat 46°11.1'N, Lon 124°11.0'W, and the Umatilla Reef lightships operated from 1899 to 1971 off Cape Alava, Washington, at Lat 48°10'N, Lon 124°50.4'W. (dates from: W. Wheeler, President, U.S. Lighthouse Society, pers. com., May 2, 1990; locations from: D. Johansen, USCG, QM1/Nav. Info., pers. com., May 7, 1990). Tidal currents at these two locations follow the general rotary pattern described in the previous paragraph, with spring and neap tides increasing the velocities by about 20 percent above average values. Following paragraphs will summarize information from the two lightships in the Washington and Oregon region as described by Bourke et al. (1971).

The Columbia River Lightship recorded weak rotary tidal currents averaging less than 15 cm/sec (0.5 ft/sec), setting 020° T at the maximum flood and setting 200° T at maximum ebb. The tidal current at flood tide is completely masked by a non-tidal current (from the river flow) which ranges in average speed from 14.6 cm/sec (0.48 ft/sec) in March to 39.0 cm/sec (1.28 ft/sec) in June. The average direction of the non-tidal current at the mouth of the Columbia River varies from 235° T from June to October, to 295° T from October to February. Greatest observed net current speed was 120 cm/sec (3.9 ft/sec) observed on a flood tide during June.

The Umatilla Reef Lightship also recorded weak rotary currents with average speeds of about 15 cm/sec (0.5 ft/sec), setting 345° T on flood and 165° T on ebb. Maximum currents are about fifteen minutes after maximum flood or ebb tides at the entrance to the Strait of Juan de Fuca. The tidal current is usually masked by wind driven currents. From November to April, the direction of average flow is 350° T at 37 cm/sec (1.2 ft/sec) with a maximum of 52 cm/sec (1.7 ft/sec) during December. From April to November the current is variable, generally setting southeast (135° T) at an average speed of about 20 cm/sec (0.7 ft/sec).

Bourke et al. (1971) also provide tables which describe the changes in speed and direction of wind driven currents which result from different wind speeds and directions at the lightships. These effects were measured approximately five miles offshore and are due primarily to coastline configuration near the location of the lightships (Bourke et al. 1971).

### Local Currents

For purposes of this report, the nearshore zone is considered to be within about 10 nm (about 18.5 km) of the coast. Many small scale local currents are found within that shallow water zone. Bourke et al. (1971) describe some of these local currents within the shallow water zone along the Washington and Oregon coast.

It is emphasized that few measurements of current velocity of these localized currents have been done. These currents fluctuate greatly in speed and direction (some local currents have been found to respond to changing forces on time scales as small as one hour), and the conditions often make calculations of average flow meaningless. "This is perhaps the reason why some offshore oil spills have been found to disperse in directions quite different from that predicted" (Bourke et al. 1971).

The forces that produce local currents are:

- winds
- main ocean currents
- tides

Waves and pressure gradients also influence local currents to a lesser extent. Wind primarily affects the surface layer, while the effect of tide extends, at least theoretically, to all levels (Bourke et al., 1971).

Local currents in the following areas are described by Bourke et al. (1971):

- Grays Harbor, Washington
- Depoe Bay, Oregon
- Newport, Oregon
- Coos Bay, Oregon

## WATER MASS CHARACTERISTICS, VERTICAL STRATIFICATION AND MIXING

Characteristics of the water masses associated with the various currents depend primarily on the direction of flow. The California Current, flowing from the north, transports low temperature, low salinity, high oxygen, high phosphate, subarctic type water from higher to lower latitudes. This water mass is characterized by a distinct halocline (a zone of rapid increase of salinity with depth) 75-150 m (250-500 ft) thick at a depth of less than 250 m (820 ft) (Hickey, 1979).

Both the Davidson Current and the California Undercurrent, flowing from the south, are characterized by warm, high salinity, equatorial type water which is low in oxygen and phosphate in the surface layers, but high in phosphate in deeper layers (Hickey, 1979).

Temperature-Salinity (T-S) diagrams for the unmodified subarctic and equatorial water are available in Pickard and Emery (1982). Sources of other T-S diagrams for water at various locations in the California Current are listed in Hickey, 1979.

Water mass characteristics of the main currents can remain relatively unchanged for great distances. The primary factors which act to change these characteristics in the Pacific Northwest include the following (Huyer and Smith, 1977):

- mixing
- changing surface temperature
- upwelling
- precipitation
- runoff (especially from the Columbia River)

The Columbia River, representing 77 percent of the total drainage (60 percent in winter, 90 percent in late summer) into the Pacific Ocean between San Francisco Bay and the Strait of Juan de Fuca, provides the principal source of modification of water masses in the Washington and Oregon region (Hickey, 1989; Strickland and Chasan, 1989).

The Columbia River plume produces a thin surface layer 5-20 m (15-65 ft) thick of less saline water (<20$^{o}$/oo). During winter the generally northerly flowing surface currents and onshore flow of the surface Eckman layer force the surface layer into a narrow strip along the Washington coast (see Figure 4-a). In summer (Figure 4-b), the effect of the southerly surface currents and resulting offshore flow of the Eckman layer cause the plume to be dispersed further off the coast of Oregon (Hickey, 1989).

Effect of the flow from the Strait of Juan de Fuca on the water masses along the Washington and Oregon coast is believed to be minimal. This is due to the relatively high salinity (31.5$^{o}$/oo), caused by tidal mixing in the Strait, and the poleward transport of the surface water outflow along the coast of Vancouver Island away from the Washington coast (Thompson et al., as cited in Landry and Hickey, 1989; Strickland and Chasan, 1989). At deeper levels, water flow is generally into the Strait from the Pacific Ocean (Hickey, 1979).

The following discussion of the vertical stratification and mixing characteristics of Pacific Northwest waters is quoted directly from Strickland and Chasan (1989), Coastal Washington - A Synthesis of Information:

> The water column ... is typically stratified into layers which may respond differently to the forces that generate currents, as momentum is transferred from one layer to another. On the Washington coast, less dense, warmer, less saline water generally forms a buoyant, stable surface layer overlying denser, colder, saltier water. ...
>
> One consequence of vertical stratification is a resistance to vertical mixing of the water column. The greater the vertical density gradient in the water column, the more force required to mix the layers of water together across a pycnocline [a layer of maximum vertical density gradient]. In general, outer Washington shelf waters are thermally stratified near the surface in summer and vertically mixed in winter, when surface water is cooled and wave action is strong. During winter the surface mixed layer extends to depths of 40-60 m [130-200 ft] on the outer shelf. The stratification found in summer is due to surface heating and decreased storm activity. The surface mixed layer depths in summer are only 10-20 m [33-66 ft]. Nearer shore on the inner

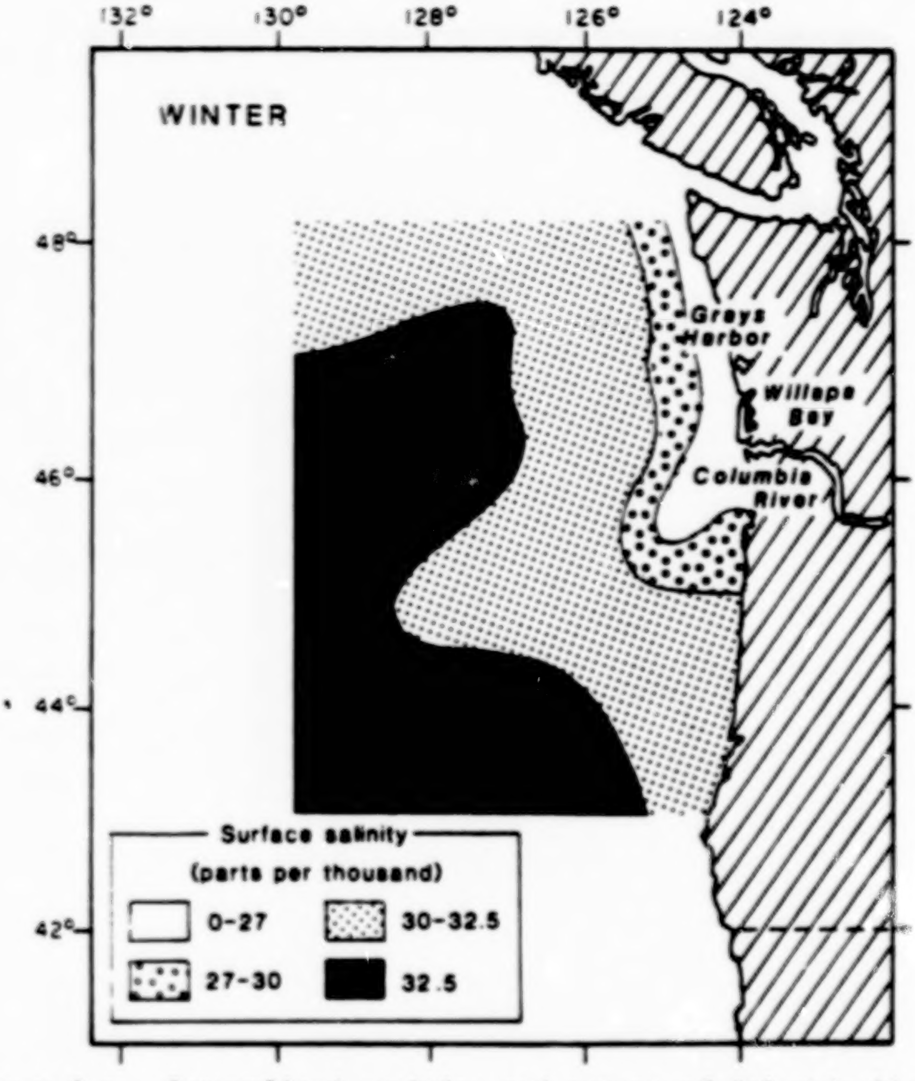

Figure 4-a. Generalized position and extent of Columbia River freshwater plume in winter (from Strickland and Chasan, 1989, as modified from Barnes et al., 1972).

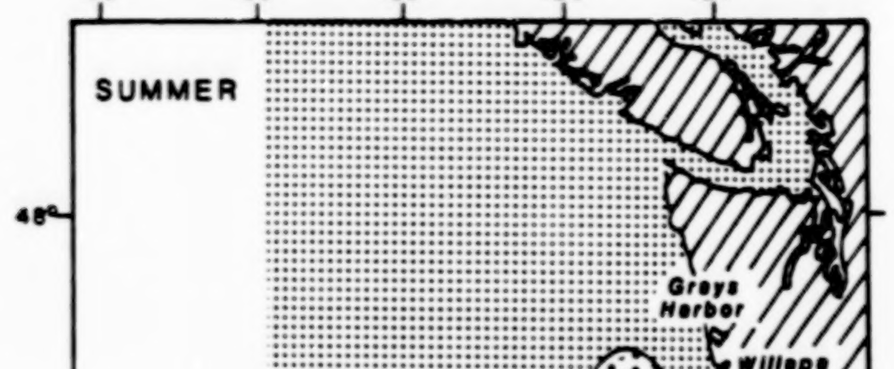

Figure 4-b. Generalized position and extent of Columbia River freshwater plume in summer (from Strickland and Chasan, 1989, as modified from Barnes et al., 1972).

> Washington shelf, however, runoff from the Columbia and other rivers reduces the depth of the mixed layer to 10 m [33 ft] or less in winter, and produces a strong pycnocline beneath the dilute river water mixture. .. Along the northern Washington coast in summer, coastal upwelling reduces the magnitude of stratification.
>
> The dissolution and dispersal of contaminants introduced into the sea surface strongly depend on mixing caused by forces that generate turbulence, such as winds and waves; factors that affect convective processes such as heating and cooling; and evaporation and precipitation, river input, and interaction among currents of varying speed and direction. The intensity of mixing in the horizontal direction is generally about a thousand times greater than that in the vertical direction .... Water currents on the shelf vary in strength and direction both horizontally and vertically. The interaction between these variable flows promotes both horizontal and vertical turbulence and mixing (Strickland and Chasan, 1989).

"The density field off Oregon has a shallow seasonal pycnocline associated with the Columbia River Plume, and a deeper permanent pycnocline ($\sigma_t$: 25.5-26.0) [density] associated with the permanent halocline (32.5-33.8$^{o}$/oo) [salinity] that is ubiquitous in the Eastern Subarctic Pacific" (Huyer, 1983).

## UPWELLING

Upwelling raises cold, nutrient rich waters into the photic zone along the coast, resulting in very high biomass productivity. Upwelling off Washington and Oregon is seasonal, due to seasonal variations in average wind direction. During summer, from about May to August, the surface Ekman layer (the surface water layer less than 20 meters thick, which moves primarily in response to wind stress at the surface) moves offshore because of favorable mean surface wind directions during that season (winds from the north nearly parallel to the coast), resulting in coastal upwelling within about 10-20 km (6-12 mi) of the coast. Downwelling occurs in winter due to the northerly flowing coastal currents and general onshore surface winds (Huyer, 1983; Strickland and Chasan, 1989; Atlas et al. 1977).

In addition to these seasonal effects, local or short-term winds and currents can result in temporary conditions producing localized short individual "upwelling events" intermittently. These short term "upwelling events" are of considerable importance to the upwelling regime off Oregon, and can occur during short-term favorable fluctuations in wind stress of several days, even in months when the mean wind stress is not favorable for upwelling (Huyer, 1983; Strickland and Chasan, 1989; Atlas et al. 1977).

Experimental evidence and models of coastal upwelling indicate that, during upwelling, water moves vertically near boundaries such as the shelf edge or the coast in response to alongshore wind stress or pressure gradient forces. Upon reaching the surface, the upwelled water is transported offshore in a thin surface layer less than 10 m (33 ft) thick. In stratified water typical of the Washington and Oregon region, the isopycnals (lines of equal density) move vertically with the upwelled water and the pycnocline (a layer of maximum vertical density gradient) tilts and moves offshore. "In summer, isopycnals from depths as great as 150 m slope upward toward the coast and intersect the surface ..." (Huyer, 1983). Water may become nearly homogeneous inshore of the pycnocline. Downwelling may occur during periods of northerly current flow near shore, resulting from onshore components of surface wind velocity and descending water near shore. (Hickey, 1989; Hermann et al., 1989; Huyer, 1983)

Current measurements during an upwelling event have shown a maximum inshore velocity just below the offshore flowing surface layer, with decreasing onshore velocity down to about 200 m (650 ft). Vertical velocity decreases rapidly with distance offshore (Huyer and Smith, 1977). Estimates of vertical velocity during an upwelling event range up to $2 \times 10^{-2}$ cm/sec ($6 \times 10^{-4}$ ft/sec). "During strong upwelling events, maximum vertical velocities are probably considerably higher" (Huyer, 1983).

Satellite derived sea surface temperature data indicate that upwelling along the coast is not uniform, but is stronger near capes and promontories which act as upwelling "centers". Near these centers of upwelling, relatively narrow offshore surface current jets are generated which can transport filaments of coastal water several hundred kilometers offshore. The width of these jets are on the order of 40 km (25 mi) with depths up to 200 m (660 ft) (Hickey, 1989; Kelly, 1985).

Studies of upwelling events in winter have indicated that individual short-term events lasting a few days can cause changes in the seasonal oceanographic regime which can persist for several months. One such event studied off Oregon "apparently caused the transition from the typical winter regime with level isopycnals and no mean vertical shear to the typical spring-summer regime with sloping isopycnals, a mean southward surface current and a strong mean vertical shear ... changes in the low frequency current fluctuations ... and changing the dominant mode of continental shelf waves from first to third mode" (Huyer, 1983).

## WAVES

Wave heights and wavelengths are important because of their effects on structures, their hazards to navigation, and their influence on the movement, dispersal, weathering, and the effectiveness of cleanup equipment for contaminants such as oil.

Wave height is the vertical distance between the crest (highest point) and the next trough (lowest point) of a wave. Since waves of many heights, lengths, and directions may be present, the most generally accepted parameter used to characterize wave heights is significant wave height, the average of the highest one-third of the waves observed (Earle and Bishop, 1984).

The U.S. Pacific Northwest is noted for heavy wave conditions comparable to the North Sea, with associated higher risks to offshore structures. Measured extremes of wave height range from 15 to 29 m (49 to 95 ft) off the coasts of Washington and Oregon (Strickland and Chasan, 1989; Oceanographic Institute of Washington, 1977).

Evidence from several sources indicates that the largest waves are produced by severe storms generated near Japan. Waves associated with cold fronts from generally westerly directions can reach significant heights 8-10 m (26-33 ft), while warm fronts, generally from the south, can produce waves with significant heights of 6-7 m (20-23 ft) (Kachel and Smith, 1989).

Corps of Engineers Wave Information Study (WIS)

A primary source of wave information for the Washington and Oregon coast is the Army Corps of Engineers Wave Information Study (WIS), a nationwide study ongoing since 1976. These are hindcast studies of wave heights, periods, and directions, based on historical meteorological data for the years 1956 through 1975, calculated at three-hour intervals. Studies based on later data are planned. The WIS wave heights hindcast using meteorological information correlate well with wave heights obtained by direct measurement. (Corson et al., 1986, 1987; J. Hubertz, US Army Corps of Engineers, pers. com., April 26, 1990).

The WIS study for the Pacific coast is in three phases (see Corson et al., 1987, for details). Phase I is a numerical hindcast of deepwater wave data from historical surface pressure and wind data for the North Pacific Ocean. Data for Phase I is computed for points on a 120 nm (222.24 km) grid covering most of the North Pacific, with 35 numbered stations adjacent to the U.S. coast selected for analysis in the 1986 report (Corson et al., 1986). There are three Phase I data sites within the Washington-Oregon Planning Area (Corson et al., 1986). Phase I data will not be discussed further in this report, since Phases II and III cover the Pacific Northwest coast in more detail.

Phase II of the WIS study of the U.S. Pacific Coast uses numerical hindcasting methods similar to those employed in Phase I. Grid points are more closely spaced in Phase II and are adjacent to the coasts of Washington, Oregon, and California, about 30-60 nm (56-112 km) from shore. Since Phase II points are only along the coast, Phase I data is used as a "seaward boundary condition" for computation of Phase II. There are 18 Phase II data sites within the Washington-Oregon Planning Area (numbered 35 through 52, south to north) plus one site (no. 53) just north of the Planning Area off the entrance to the Strait of Juan de Fuca (Corson et al., 1987). Phase II sites off the coast of Washington and Oregon are shown in Figures 5-a, b, and c.

Phase III of the WIS study generated wave information using a different procedure than previous phases. Phases I and II used a "numerical wave model which simultaneously generated, propagated, and transformed waves over a discrete grid ... The phase III wave data were generated assuming straight

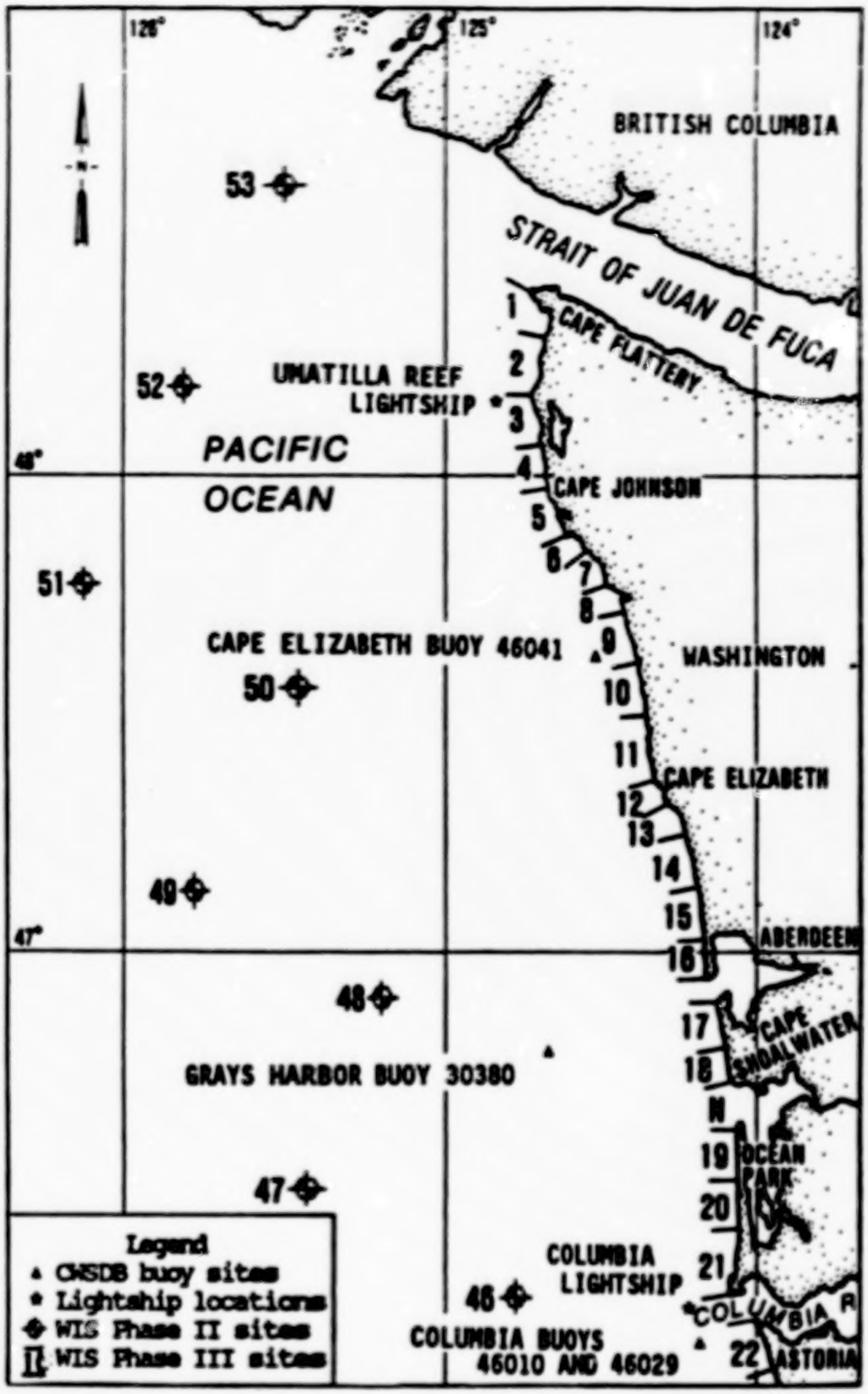

Figure 5-a. Locations of Wave Information Study Phase II sites, Phase III shoreline segments, Coastal Wave Statistical Data Base Buoys, and former Lightship locations on the Washington Coast. (base map from Jensen et al., 1989)

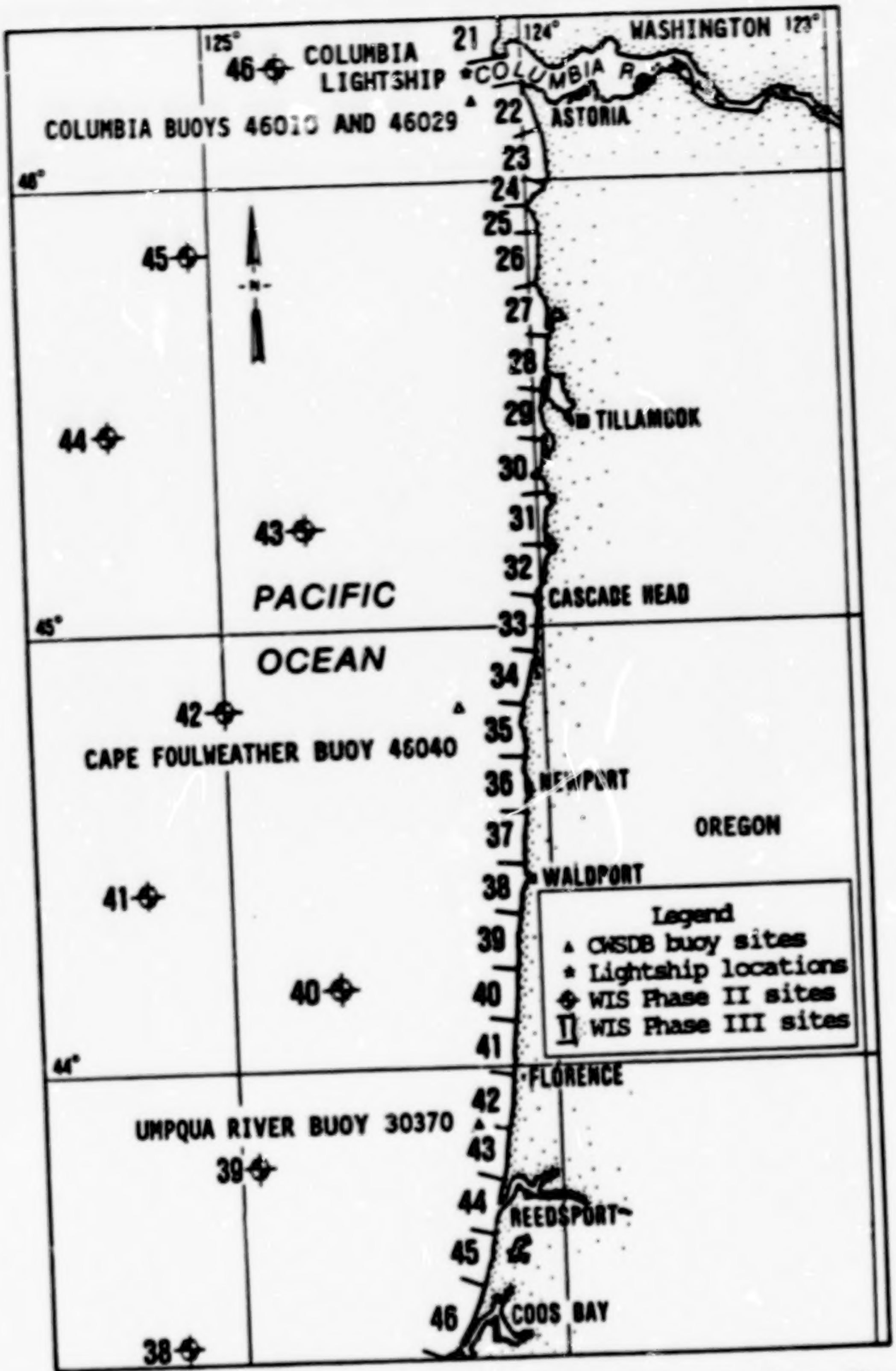

Figure 5-b. Locations of Wave Information Study Phase II sites, Phase III shoreline segments, Coastal Wave Statistical Data Base Buoys, and former Lightship locations on the northern Oregon coast. (base map from Jensen et al., 1989)

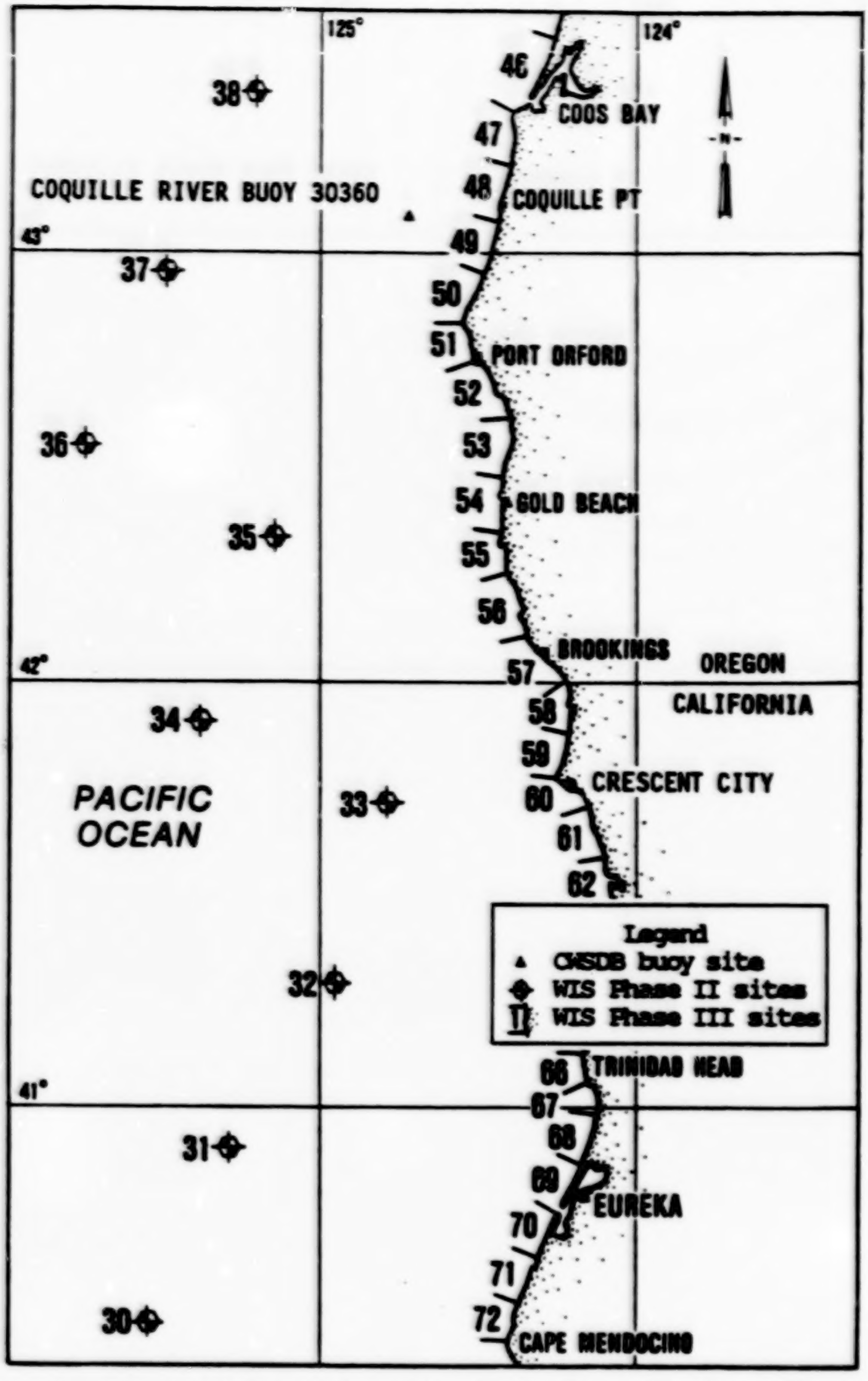

Figure 5-c. Locations of Wave Information Study Phase II sites, Phase III shoreline segments, Coastal Wave Statistical Data Base Buoys, and former Lightship locations on the southern Oregon coast. (base map from Jensen et al., 1989)

and parallel bottom contours, with a uniform slope offshore. Sheltering of waves by large-scale coastal features was subjectively determined. Smaller scale coastal features were ignored ... Water level variations due to storm surge and tide are not included" (Jensen et al., 1989).

Phase III data was calculated for 132 shoreline segments 10 miles (16 km) in length, from the US-Canadian border to Point Conception, California, rather than for discrete grid points as in Phases I and II. There are 58 Phase III shoreline segments within the Washington-Oregon Planning Area (numbered 1 through 58, north to south). Phase III hindcasts wave information within about 30 nm (55.6 km) from shore and in water depths less than 10 m (33 ft) (W. Corson, US Army Corps of Engineers, pers. com., April 26, 1990).

The tables in this section are organized to allow comparisons of Corps of Engineers WIS Phase III (nearshore) waves and Phase II (offshore) wave data, derived from meteorological information, with Minerals Management Service Coastal Wave Statistical Data Base (CWSDB) data taken directly from data buoys (to be discussed in the next section). The MMS system of data buoys is approximately intermediate between the two WIS Phases, in terms of distance from shore and depth of water. Although no direct comparison of data for particular times is possible (dates of data collection do not coincide), it is possible to compare wave extremes, return period information, and overall summaries (two dimensional tables) of wave heights and periods from the two systems.

The tables in this section include the following information:

- Tables 1-a and 1-b summarize WIS Phase II hindcasts of extreme waves for return periods of 5, 10, 20, and 50 years for Washington and Oregon. The Phase II sites off Washington and Oregon were used in Tables 1-a and 1-b, respectively. For Washington, the highest waves were at site 51, off the Hoh Head/Teahwhit Head area. For Oregon, the highest waves were at sites 35, 36, and 37, off the Cape Blanco area. In Tables 1-a and 1-b, data was combined for all Phase II sites off the coast of each state.

- Similar data for individual Phase II sites near MMS CWSDB Buoys is given in Table 2.

- In Table 3, WIS Phase III hindcasts of wave heights are given for some Phase III land segments for return periods of 1, 3, 5, 7, 10, and 21 years. WIS land segments for both Washington and Oregon are combined in Table 3. The data in Phase III tables are for water less than 10 m (about 33 ft) deep along the coast, as previously described.

- Table 4 is a two dimensional table summarizing WIS Phase III data for percentages of waves with various combinations of wave height and period. Note that the percentages do not add up to exactly 100% because of round-off error. Locations of WIS Phase III land segments are plotted in Figures 5-a, b, and c.

Table 1-a. Maximum significant wave heights for various return periods for WIS Phase II sites off Washington. Based on data[1] from hindcasts by Army Corps of Engineers Wave Information Study (WIS) for the 8 Phase II sites off the Washington coast.[2]

| Return Period (yr) | $H_{sig}$[3] (m) | Lower $H_{sig}$ Error Limit (m) | Upper $H_{sig}$ Error Limit (m) | WIS Location Number[4] |
|---|---|---|---|---|
| 5 | 10.8 | 10.6 | 11.9 | 51 |
| 10 | 11.4 | 10.2 | 11.5 | 51 |
| 20 | 12.0 | 11.7 | 13.1 | 51 |
| 50 | 13.2 | 12.5 | 14.0 | 51 |

Source: Corson et al. (1987). For data from 1956 to 1975.

[1] Highest value from Phase II sites no. 46 to 53 (8 sites), located off the Pacific coast from the Columbia River to Cape Flattery (northwest Washington). Note that site 53 is outside the planning area off the entrance to the Strait of Juan de Fuca. See Figure 5-a for locations.

[2] Phase II data sites are about 30-60 nm (56-112 km) offshore.

[3] Significant wave height.

[4] Site 51 was the Phase II site with the highest hindcast significant wave height extremes off the Washington coast.

Table 1-b. Maximum significant wave heights for various return periods for WIS Phase II sites off Oregon. Based on data[1] from hindcasts by Army Corps of Engineers Wave Information Study (WIS) for the 11 Phase II sites off the Oregon coast[2].

| Return Period (yr) | $H_{sig}$[3] (m) | Lower $H_{sig}$ Error Limit (m) | Upper $H_{sig}$ Error Limit (m) | WIS Location Number[4] |
|---|---|---|---|---|
| 5 | 10.9 | 10.6 | 12.4 | 36,37 |
| 10 | 11.7 | 11.4 | 13.3 | 36,37 |
| 20 | 12.6 | 12.1 | 14.5 | 35,36,37 |
| 50 | 14.5 | 13.5 | 16.1 | 35 |

Source: Corson et al. (1987). For data from 1956 to 1975.

[1] Highest value from Phase II sites 35 to 45 (11 sites), located off the Pacific coast from southern Oregon to the Columbia River. See Figures 5-b and 5-c for locations.

[2] Phase II data sites are about 30-60 nm (56-112 km) offshore.

[3] Significant wave height.

[4] Sites 36 and 37 were the Phase II sites with the highest significant wave height extremes along the Oregon coast for 5 and 10 year return periods. Sites 35, 36, and 37 were highest Phase II sites for 20 year return period. Site 35 was highest Phase II site for 50 year return period.

Table 2. Significant wave heights for various return periods for WIS Phase II sites[1] near MMS Coastal Wave Statistical Data Buoy sites[1] off Washington and Oregon. Data from hindcasts by Army Corps of Engineers Wave Information Study (WIS) Phase II.

| WIS Location Number | MMS Buoy No. | Return Period (yr) | $H_{sig}$[2] (m) | Lower $H_{sig}$ Error Limit (m) | Upper $H_{sig}$ Error Limit (m) |
|---|---|---|---|---|---|
| 50 | 46041 | 5 | 9.5 | 9.4 | 10.4 |
| | | 10 | 10.0 | 9.8 | 10.9 |
| | | 20 | 10.5 | 10.3 | 11.5 |
| | | 50 | 11.5 | 11.0 | 12.2 |
| 48 | 30380 | 5 | 9.2 | 9.0 | 10.1 |
| | | 10 | 9.7 | 9.5 | 10.7 |
| | | 20 | 10.2 | 10.0 | 11.2 |
| | | 50 | 11.2 | 10.7 | 12.0 |
| 46 | 46010 and 46029 | 5 | 9.1 | 8.9 | 10.0 |
| | | 10 | 9.6 | 9.4 | 10.5 |
| | | 20 | 10.1 | 9.8 | 11.0 |
| | | 50 | 11.1 | 10.5 | 11.8 |
| 42 | 46040 | 5 | 9.9 | 9.8 | 10.9 |
| | | 10 | 10.4 | 10.2 | 11.4 |
| | | 20 | 11.0 | 10.7 | 11.9 |
| | | 50 | 12.0 | 11.4 | 12.7 |
| 40 | 30370 | 5 | 10.3 | 10.0 | 12.0 |
| | | 10 | 11.2 | 10.8 | 12.9 |
| | | 20 | 12.1 | 11.7 | 14.0 |
| | | 50 | 14.1 | 13.0 | 15.6 |
| 38 | 30360 | 5 | 10.5 | 10.2 | 11.8 |
| | | 10 | 11.2 | 10.9 | 12.6 |
| | | 20 | 11.9 | 11.6 | 13.4 |
| | | 50 | 13.4 | 12.6 | 14.5 |

Source: Corson et al. (1987). For data from 1956 to 1975.

[1] Phase II data sites are about 30 to 60 nm (56 to 112 km) offshore. Phase II sites and CWSDB buoy locations are shown in Figures 5-a, b, and c.

[2] Significant wave height.

Table 3. Hindcast significant wave heights (meters) at representative Army Corps of Engineers Wave Information Study (WIS) Phase III (shallow water coastal segment) locations in the Washington-Oregon Planning Area[1], for various return periods.

| Station No.[2] | Return Period (years) | | | | | |
|---|---|---|---|---|---|---|
| | 21 | 10 | 7 | 5 | 3 | 1 |
| 1 | 7.5 | 7.3 | 7.3 | 7.3 | 6.7 | 6.5 |
| 3 | 7.5 | 7.3 | 7.3 | 7.3 | 6.7 | 6.6 |
| 5 | 7.7 | 7.7 | 7.4 | 7.4 | 7.1 | 6.7 |
| 8 | 6.9 | 6.9 | 6.8 | 6.8 | 6.7 | 6.3 |
| 9[3] | 7.0 | 7.0 | 6.7 | 6.7 | 6.5 | 6.2 |
| 10 | 7.0 | 6.9 | 6.8 | 6.8 | 6.5 | 6.2 |
| 13 | 7.0 | 6.9 | 6.8 | 6.7 | 6.6 | 6.2 |
| 16 | 7.2 | 7.1 | 6.9 | 6.8 | 6.6 | 6.3 |
| 17[4] | 7.1 | 7.0 | 6.9 | 6.8 | 6.6 | 6.2 |
| 18 | 7.2 | 7.1 | 6.9 | 6.8 | 6.6 | 6.3 |
| 21 | 7.3 | 6.9 | 6.9 | 6.7 | 6.6 | 6.3 |
| 22[5] | 7.1 | 6.9 | 6.8 | 6.8 | 6.5 | 6.3 |
| 23 | 7.4 | 7.1 | 7.0 | 6.8 | 6.6 | 6.3 |
| 25 | 7.4 | 7.2 | 7.1 | 6.9 | 6.8 | 6.5 |
| 27 | 7.4 | 7.3 | 7.2 | 6.9 | 6.9 | 6.6 |
| 32 | 7.3 | 7.2 | 7.2 | 7.0 | 6.8 | 6.5 |
| 34 | 7.2 | 7.2 | 7.0 | 7.0 | 6.9 | 6.6 |
| 35[6] | 7.3 | 7.3 | 7.3 | 7.1 | 7.0 | 6.6 |
| 36 | 7.3 | 7.3 | 7.2 | 7.1 | 7.0 | 6.6 |
| 41 | 7.4 | 7.2 | 7.2 | 7.0 | 6.8 | 6.5 |
| 42[7] | 7.3 | 7.2 | 7.2 | 7.0 | 6.8 | 6.5 |
| 43[7] | 7.4 | 7.2 | 7.1 | 7.1 | 6.9 | 6.6 |
| 44 | 7.3 | 7.2 | 7.1 | 7.0 | 6.8 | 6.6 |
| 47 | 7.7 | 7.1 | 7.1 | 7.0 | 6.9 | 6.6 |
| 48[8] | 7.4 | 7.1 | 7.1 | 6.9 | 6.8 | 6.3 |
| 49 | 7.4 | 7.0 | 7.0 | 6.9 | 6.8 | 6.5 |
| 52 | 8.0 | 7.7 | 7.1 | 7.1 | 6.9 | 6.5 |
| 55 | 7.8 | 7.6 | 7.1 | 7.0 | 6.9 | 6.6 |
| 58 | 7.8 | 7.0 | 7.0 | 7.0 | 6.9 | 6.5 |

Source: Jensen at al. (1989). Hindcast from data for 1956 to 1975.

[1] There are 58 WIS Phase III stations in the Washington-Oregon Planning area numbered from 1 (at Cape Flattery, Washington) to 58 (at the Oregon-California border). These represent approximately 10 mile (16.1km) segments of coastline out to water depths of about 10 m (33 ft). See Figures 5-a, b, and c for locations of these segments.

[2] The WIS station numbers are used. See Figure 5-a, b, and c for locations.

[3] MMS CWSDB Cape Elizabeth Buoy 46041 offshore this area at 42 m depth.

[4] MMS CWSDB Grays Harbor Buoy 30380 offshore this area at 111.6 m depth.

[5] MMS CWSDB Columbia Buoys 46010 & 46029 offshore this area at 60 m depth.

[6] MMS CWSDB Cape Foulweather Buoy 46040 offshore this area at 110 m depth.

[7] MMS CWSDB Umpqua River Buoy 30370 offshore these areas at 42 m depth.

[8] MMS CWSDB Coquille River Buoy 30360 offshore this area at 65.8 m depth.

Table 4. Wave heights and periods, percent occurrence within each range, at representative Army Corps of Engineers Wave Information Study (WIS) Phase III (shallow water) coastline segments in the Washington-Oregon Planning Area.

| Site * | Height (m) | Period Range (sec) | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 4.4-6.0 | 6.1-8.0 | 8.1-9.5 | 9.6-10.5 | 10.6-11.7 | 11.8-13.3 | 13.4-15.3 | 15.4-18.1 | 18.2 & up | % ↓ |
| 3-III | 0.00-0.49 | .04 | .01 | .01 | | | .01 | | | .01 | .08 |
| | 0.50-0.99 | .60 | 3.00 | 2.23 | .45 | .07 | .01 | | | .02 | 6.38 |
| | 1.00-1.49 | 1.30 | 4.50 | 8.32 | 2.90 | .96 | .25 | .01 | | | 18.24 |
| | 1.50-1.99 | 1.42 | 1.93 | 5.85 | 5.09 | 3.12 | 1.19 | .16 | .03 | | 18.79 |
| | 2.00-2.49 | .26 | 1.71 | 2.00 | 4.03 | 4.39 | 2.10 | .37 | .02 | | 14.88 |
| | 2.50-2.99 | | .61 | .94 | 1.44 | 4.41 | 3.47 | .81 | .02 | | 11.70 |
| | 3.00-3.49 | | .16 | .55 | .79 | 2.78 | 4.01 | 1.38 | .04 | | 9.71 |
| | 3.50-3.99 | | .01 | .24 | .31 | 1.41 | 3.63 | 1.86 | .07 | | 7.53 |
| | 4.00-4.49 | | | .09 | .13 | .70 | 2.32 | 2.02 | .15 | | 5.41 |
| | 4.50-4.99 | | | .01 | .05 | .22 | 1.05 | 1.62 | .15 | | 3.10 |
| | 5.00+ | | | | .01 | .07 | .65 | 2.32 | .71 | | 3.76 |
| | percent → | 3.62 | 11.93 | 20.24 | 15.20 | 18.13 | 18.69 | 10.55 | 1.19 | .03 | |
| 28-III | 0.00-0.49 | .01 | .01 | | | | .01 | | | | .03 |
| | 0.50-0.99 | .23 | 1.08 | 1.74 | .38 | .12 | .03 | .02 | | .04 | 3.64 |
| | 1.50-1.99 | 1.45 | 1.71 | 4.70 | 4.71 | 3.43 | 1.55 | .22 | .05 | | 17.82 |
| | 2.00-2.49 | .16 | 1.32 | 1.28 | 3.57 | 4.64 | 2.84 | .60 | .06 | | 14.47 |
| | 2.50-2.99 | | .47 | .49 | 1.29 | 4.49 | 4.50 | 1.18 | .07 | .02 | 12.51 |
| | 3.00-3.49 | | .10 | .36 | .50 | 2.52 | 5.62 | 1.94 | .12 | | 11.16 |
| | 3.50-3.99 | | | .16 | .25 | 1.24 | 4.41 | 2.74 | .17 | .01 | 8.98 |
| | 4.00-4.49 | | | .05 | .09 | .41 | 2.78 | 2.77 | .27 | | 6.37 |
| | 4.50-4.99 | | | | .03 | .14 | 1.14 | 2.52 | .28 | | 4.11 |
| | 5.00+ | | | | | .06 | .54 | 3.47 | 1.13 | | 5.20 |
| | percent → | 2.78 | 7.47 | 15.67 | 13.97 | 18.25 | 23.74 | 15.53 | 2.16 | .07 | |
| 52-III | 0.00-0.49 | .13 | .12 | .03 | | | | | | | .28 |
| | 0.50-0.99 | .97 | 2.52 | 2.85 | .76 | .19 | .10 | .03 | .01 | | 7.43 |
| | 1.00-1.49 | 1.05 | 3.58 | 8.15 | 5.01 | 2.53 | .93 | .12 | .01 | | 21.38 |
| | 1.50-1.99 | .25 | 1.28 | 2.72 | 4.96 | 5.17 | 2.38 | .38 | .01 | | 17.15 |
| | 2.00-2.49 | .03 | .81 | .80 | 1.74 | 4.34 | 4.45 | 1.00 | .07 | | 12.25 |
| | 2.50-2.99 | | .42 | .74 | .66 | 2.55 | 5.36 | 1.91 | .14 | .01 | 11.79 |
| | 3.00-3.49 | | .12 | .69 | .44 | 1.22 | 3.88 | 2.65 | .19 | | 9.19 |
| | 3.50-3.99 | | .02 | .49 | .47 | .66 | 2.52 | 2.74 | .24 | .01 | 7.15 |
| | 4.00-4.49 | | | .15 | .37 | .47 | 1.43 | 2.35 | .26 | | 5.03 |
| | 4.50-4.99 | | | .02 | .18 | .35 | .56 | 1.66 | .34 | | 3.11 |
| | 5.00+ | | | | .03 | .30 | .72 | 1.90 | .83 | | 3.78 |
| | percent → | 2.43 | 8.87 | 16.64 | 14.62 | 17.78 | 22.33 | 14.74 | 2.10 | .03 | |

Source: Jensen et al. (1989). For data from 1956 to 1975.
* Locations: 3-Cape Alava; 28-Tillamook; 52 - Cape Blanco (Fig. 5-a,b, & c).

The tables and figures in this section have provided a summary of Corps of Engineers WIS wave data available for the Washington-Oregon Planning Area. A large amount of detailed WIS information is available for the coast of Washington and Oregon.

The approach used by WIS is a statistical analysis of climatological data which is used to determine probable wave heights over large areas. The Minerals Management Service Coastal Wave Statistical Data Base (CWSDB), described in the next section, uses a system of data buoys, as well as other available wave data, to provide high quality wave information over much more limited areas than the WIS study. Both approaches have been shown to be valid for their intended uses.

## Minerals Management Service Coastal Wave Statistical Data Base (CWSDB)

"A Coastal Wave Statistical Data Base (CWSDB) for the U.S. west coast has been developed to rapidly and efficiently provide ocean wave statistics based on high quality ocean wave measurements for applications of the Minerals Management Service Pacific OCS Region. The data base operates on a super-microcomputer system at the offices of the Minerals Management Service, Pacific OCS Region. The CWSDB includes wave information ... for locations off the west coast of the continental U.S." (DOI, 1988a).

Data from seven buoys along the coasts of Washington and Oregon are currently used by the CWSDB. Locations of CWSDB buoys are given in Table 5-a and Figure 5-a, b, and c. Table 5-b gives dates of data collection and operation of CWSDB buoys. Wave extremes calculated from combined data from the seven Pacific Northwest buoys for various return periods are given in Table 6-a. Wave extremes calculated for individual CWSDB buoys are given in Table 6-b. Wave statistics for the years 1979 through 1987 for the complete data set, and for the months of January and July, for combined data from Pacific Northwest buoys, is given in Table 7.

## Comparison of WIS and CWSDB Wave Information

Comparisons between WIS Phase III hindcast wave calculations and actual wave measurements were conducted by the Corps of Engineers in an effort to verify the WIS model. Although data were not available for exactly the same times and places as those calculated for Phase III, comparisons between mean values are possible. WIS calculations were based on information from 1956 to 1975, while actual measurements were available only since 1979.

One comparison done by Jensen et al. (1989) uses NOAA buoy 46010 and WIS Phase III site 22, at the mouth of the Columbia River. Data from this buoy is also used in the CWSDB data base. Location of buoy 46010 and nearby WIS Phase III sites are provided in Figure 5-b. For NOAA buoy 46010 and WIS Phase III site 22, the distribution of mean monthly significant wave heights were similar, with the major difference being the winter WIS monthly means. These were up to one meter higher than those calculated from buoy data. It

Table 5-a. Minerals Management Service Coastal Wave Statistical Data Base (CWSDB) buoys[1] in the Washington-Oregon Planning Area.

| ID no. | Site name | Lat | Lon | Depth (m) |
|---|---|---|---|---|
| 30360 | Coquille River | 43.11N | 124.53W | 65.8 |
| 30370 | Umpqua River | 43.86N | 124.24W | 42.0 |
| 30380 | Grays Harbor | 46.81N | 124.59W | 111.6 |
| 46010 | Columbia | 46.20N | 124.20W | 60.0 |
| 46029 | Columbia | 46.20N | 124.20W | 60.0 |
| 46040 | Cape Foulweather | 44.80N | 124.30W | 110.0 |
| 46041 | Cape Elizabeth | 47.60N | 124.50W | 42.0 |

Source: Minerals Management Service Coastal Wave Statistical Data Base (see DOI, 1988a).

[1] Data from buoys maintained by various agencies are used in the CWSDB.

Table 5-b. Dates of data collection from buoys used in the Minerals Management Service Coastal Wave Statistical Data Base (CWSDB) in the Pacific Northwest. (Numbers in table indicate months).

| Year | Buoy Number | | | | | | |
|---|---|---|---|---|---|---|---|
| | 30360 | 30370 | 30380 | 46010 | 46029 | 46040 | 46041 |
| 1979 | | | | 7 & 11 | | | |
| 1980 | 4 | | | all | | | |
| 1981 | 12 | 11 | | all | | | |
| 1982 | all | | 1-7 & 10-12 | 1-3 & 8-12 | | | |
| 1983 | 8-9 | | 2 & 10 | all | 12 | | |
| 1984 | 8-12 | 6-12 | 5 | 1-3 & 8-12 | 4-12 | | |
| 1985 | all | | 6-8 & 10-12 | 1-10 & 12 | 1-4 | | |
| 1986 | 1-10 | | 1-4 | | | | |
| 1987 | | | | | | 5-12 | 5-12 |

Sources: DOI, 1988c and CWSDB data.

Table 6-a. Wave extremes from combined data from seven Minerals Management Service Coastal Wave Statistical Data Base (CWSDB) locations on the coast of Washington and Oregon for specified return periods.

| Return Period (yr) | $H_{sig}$[1] (m) | Lower $H_{sig}$ Error Limit (m) | Upper $H_{sig}$ Error Limit (m) | $T_{peak}$[2] (s) | $T_{zero}$[3] (s) |
|---|---|---|---|---|---|
| 1 | 8.0 | 7.7 | 8.4 | 14.2 | 10.1 |
| 5 | 9.1 | 8.6 | 9.5 | 14.8 | 10.4 |
| 10 | 9.4 | 8.9 | 10.0 | 15.0 | 10.4 |
| 25 | 9.9 | 9.2 | 10.6 | 15.2 | 10.5 |
| 50 | 10.2 | 9.4 | 11.1 | 15.4 | 10.6 |
| 100 | 10.5 | 9.6 | 11.6 | 15.5 | 10.7 |

See Table 6-b for notes and source.

Table 6-b. Representative wave extremes for individual Minerals Management Service Coastal Wave Statistical Data Base (CWSDB) locations on the coast of Washington and Oregon for specified return periods.

| Site Loc. | Return Period (yr) | $H_{sig}$[1] (m) | Lower $H_{sig}$ Error Limit (m) | Upper $H_{sig}$ Error Limit (m) | $T_{peak}$[2] (s) | $T_{zero}$[3] (s) |
|---|---|---|---|---|---|---|
| 30380[4] | 1 | 7.0 | 6.6 | 7.5 | 12.2 | 9.6 |
| | 5 | 8.2 | 7.6 | 8.9 | 13.2 | 10.1 |
| | 10 | 8.6 | 7.8 | 9.5 | 13.6 | 10.3 |
| | 25 | 9.1 | 8.1 | 10.2 | 14.0 | 10.5 |
| | 50 | 9.4 | 8.2 | 10.8 | 14.3 | 10.6 |
| | 100 | 9.6 | 8.3 | 11.3 | 14.5 | 10.7 |
| 46010[4] | 1 | 8.4 | 8.0 | 8.8 | 14.8 | 10.3 |
| | 5 | 9.4 | 8.9 | 8.9 | 15.6 | 10.8 |
| | 10 | 9.7 | 9.1 | 10.4 | 15.9 | 11.0 |
| | 25 | 10.2 | 9.4 | 11.0 | 16.2 | 11.2 |
| | 50 | 10.5 | 9.5 | 11.5 | 16.5 | 11.4 |
| | 100 | 10.8 | 9.7 | 11.9 | 16.7 | 11.5 |
| 30360[4] | 1 | 7.2 | 6.7 | 7.6 | 12.5 | 10.1 |
| | 5 | 8.3 | 7.7 | 8.9 | 11.8 | 9.4 |
| | 10 | 8.7 | 7.9 | 9.5 | 11.6 | 9.2 |
| | 25 | 9.2 | 8.2 | 10.2 | 11.4 | 9.0 |
| | 50 | 9.5 | 8.3 | 10.8 | 11.3 | 8.8 |
| | 100 | 9.8 | 8.4 | 11.3 | 11.1 | 8.7 |

Source (Tables 6-a and 6-b): Minerals Management Service Coastal Wave Statistical Data Base, 1979 through 1989 data (see DOI, 1988a).

[1] Significant Wave Height (see Appendix C).

[2] Wave period of maximum energy (see Appendix C).

[3] Zero Crossing Wave Period (see Appendix C).

[4] Locations: See Table 5-a and Figures 5-a,b, and c.

Table 7. Wave statistics of combined data from seven Minerals Management Service Coastal Wave Statistical Data Base (CWSDB) buoys on the coast of Washington and Oregon.

| | $H_{sig}$ (m) | $T_{peak}$ (sec) | $T_{zero}$ (sec) | $E_{t(6)}$ (%)[1] | $E_{t(10)}$ (%)[2] |
|---|---|---|---|---|---|
| Mean | 2.18 | 10.26 | 7.33 | 19.55 | 59.52 |
| July only | 1.33 | 8.11 | 5.90 | 32.01 | 83.93 |
| January only | 2.71 | 11.59 | 8.29 | 12.43 | 44.68 |
| Standard deviation | 1.17 | 2.95 | 2.02 | 15.62 | 24.85 |
| July only | 0.50 | 2.20 | 1.34 | 17.39 | 16.70 |
| January only | 1.15 | 2.87 | 2.13 | 11.86 | 21.05 |
| Minimum | 0.23 | 0.00 | 2.90 | 0.00 | 1.00 |
| July only | 0.43 | 2.80 | 3.10 | 3.00 | 20.50 |
| January only | 0.23 | 2.90 | 3.00 | 0.00 | 5.00 |
| Maximum | 0.44 | 25.00 | 18.00 | 100.00 | 100.00 |
| July only | 3.95 | 20.00 | 14.00 | 98.10 | 100.00 |
| January only | 8.27 | 20.00 | 16.00 | 100.00 | 100.00 |
| No. of observations | 70,767 | 69,354 | 70767 | 70767 | 70767 |
| July only | 5528 | 5528 | 5528 | 5528 | 5528 |
| January only | 4868 | 4868 | 4868 | 4868 | 4868 |
| No. of site days | 4402 | 4344 | 4402 | 4402 | 4402 |
| July only | 329 | 329 | 329 | 329 | 329 |
| January only | 330 | 330 | 330 | 330 | 330 |

Source: Minerals Management Service Coastal Wave Statistical Data Base, combined data for 1979-1989.

1 and 2: $E_{t(6)}$ and $E_{t(10)}$ are a means of expressing the energy distribution (with respect to wave period) of a wave form made up of waves having different periods. These parameters express, respectively, the percent of total energy in waves with periods of less than 6 seconds and the percent of total energy in waves with periods greater than 10 seconds.

was speculated that more extreme events could occur in the much longer WIS time series to raise the WIS winter means.

Jensen et al. (1989) summarize their comparison studies with the conclusion that WIS Phase III hindcasts are most useful in characterizing the wave height, period, and direction at sites which have characteristics similar to the model assumptions of "straight, unsheltered coastlines with simple offshore bathymetry and the absence of reefs, shoals, and rivers which might affect local wave conditions."

Average significant wave heights for August and December (always the lowest and highest monthly average significant wave heights, respectively) and the overall average significant wave heights for each site for WIS Phase III and CWSDB data are plotted in Figure 6-a. It is interesting to note that between 42° North and 48° North latitude the average wave heights do not vary much by latitude, but the variation between the highest month (December) and the lowest month (August) is quite significant (greater than 2:1). Seasonal average significant wave heights for three CWSDB sites (Figure 6-b) show a typical pattern, with winter average heights about twice the summer average heights.

Maximum significant wave heights from WIS hindcasts in the Pacific Northwest are considerably higher than the average heights. For Phase II sites, maximum heights up to 13 m (43 ft) were hindcast. Phase III shallow water shoreline segments have maximum heights up to about 8.0 m (26 ft). These maxima were along the southern Oregon coast, with other Pacific Northwest coastal areas having slightly lower maximum extremes (Table 6-b).

Difference between Phase II and III maxima are primarily due to the differences in water depth. The CWSDB observations of maximum significant wave height were generally in the 8-10 m (26-33 ft) range, which is between those of WIS Phase II and III hindcasts. This is probably because of the intermediate depths at these CWSDB stations. The low maximum wave height (about 7 m or 23 ft) observed at the Umpqua River Buoy may be due to the relatively short time series of observations at the site (see Table 5-b) and to the relatively shallow water compared to most other CWSDB sites (see Table 5-a).

Maximum hindcast significant wave heights for WIS Phases II and III and maximum observed significant wave heights at CWSDB sites are illustrated in Figure 6-c. Phase III hindcasts for shoreline segments are plotted as a line because of their continuity along the coast, while Phase II and CWSDB sites are plotted as discreet points in Figure 6-c because they are not a continuous distribution. Note that there is an apparent trend of decreasing height with latitude in Phase II data which is not so obvious for Phase III data.

## Nearshore Wave Data

Some sources of wave data for nearshore ocean waves include wave measurements based on seismic techniques. Since the mid-1970's, nearshore wave data has been collected at seven U.S. Coast Guard stations along the coast of Washington and Oregon using land-based seismometers. This data is reported at 3-hour intervals to the National Weather Service, along with weather related data collected at the stations (Zopf et al., 1978; USCG, Chetco River Station, pers. com., April 25, 1990).

Similar seismic wave data has been collected by Oregon State University at the Marine Science Center in Newport, Oregon, continuously since about 1972. This has been shown to correlate well with wave observations off Yaquina Bay in depths of about 12 m (40 ft) (Creech, 1977). Much of the

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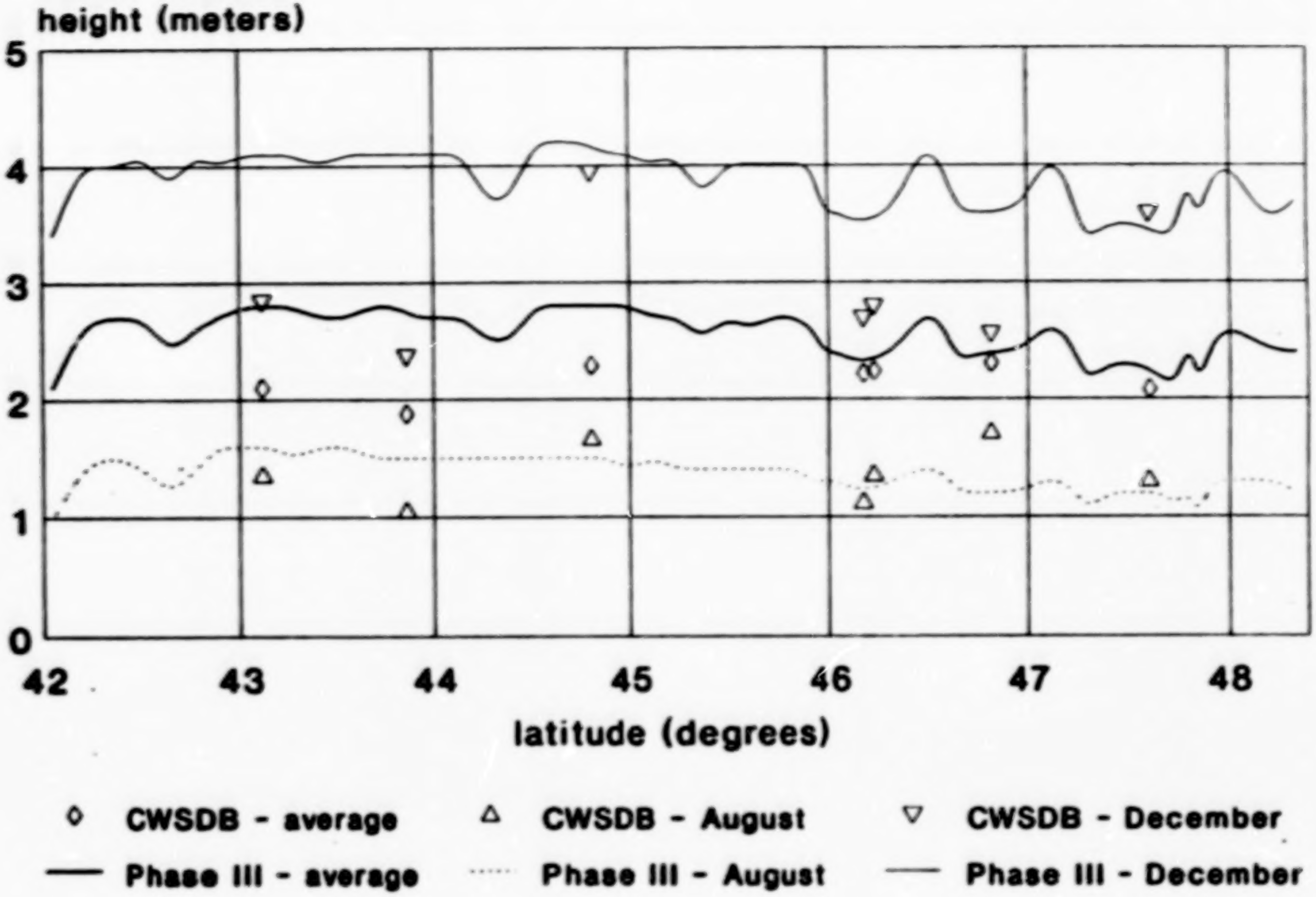
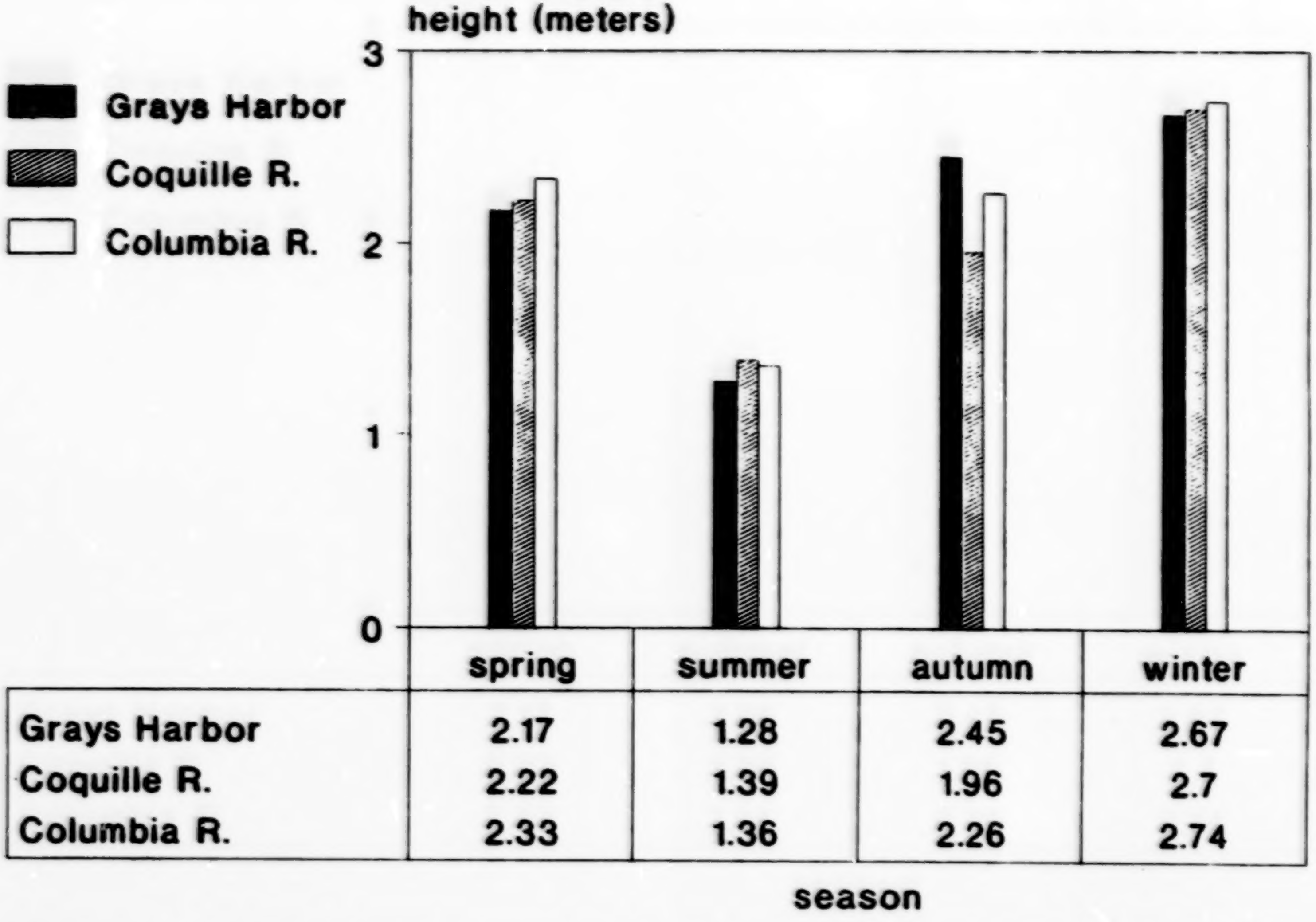


Figure 6-a. Average significant wave heights hindcast at WIS Phase III shoreline segments and observed at CWSDB data buoy sites along the coast of Washington and Oregon (Source: Jensen et al., 1989; and the Coastal Wave Statistical Data Base, Minerals Management Service, Pacific OCS Region, Los Angeles, CA)



| | spring | summer | autumn | winter |
|---|---|---|---|---|
| Grays Harbor | 2.17 | 1.28 | 2.45 | 2.67 |
| Coquille R. | 2.22 | 1.39 | 1.96 | 2.7 |
| Columbia R. | 2.33 | 1.36 | 2.26 | 2.74 |

Figure 6-b. Average significant wave heights at three Coastal Wave Statistical Data Base (CWSDB) data buoys along the coast of Washington and Oregon, by seasons. Buoy numbers: Grays Harbor - 30380, Coquille River - 30360, and Columbia River - 46010 and 46029. Source: Coastal Wave Statistical Data Base, Minerals Management Service, Pacific OCS Region, Los Angeles, California.

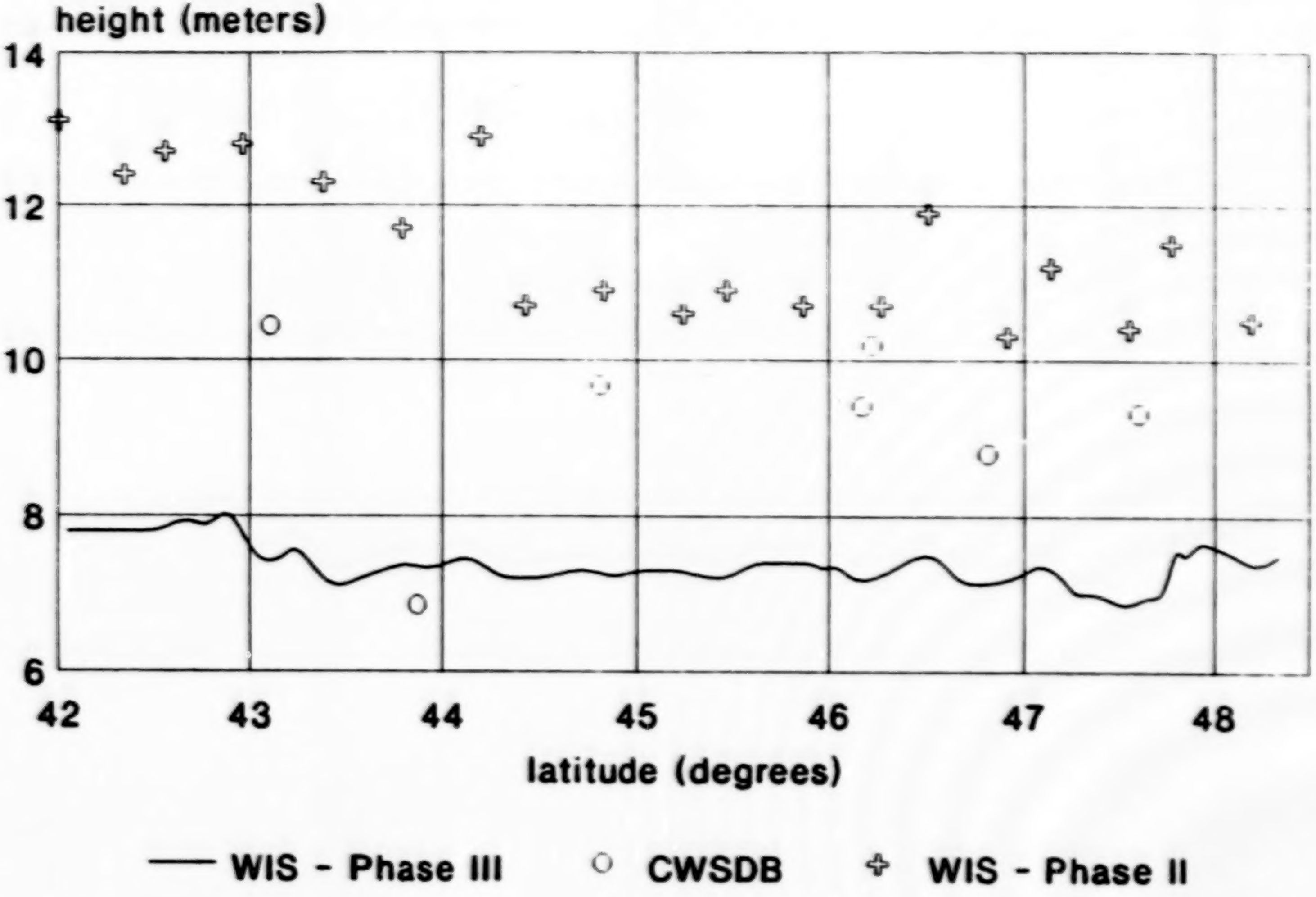


Figure 6-c. Maximum significant wave heights hindcast at WIS Phase III shoreline segments, Phase II sites, and observed at CWSDB data buoy sites along the coast of Washington and Oregon. Sources: Jensen et al. (1989), Corson et al. (1987), and Coastal Wave Statistical Data Base, Minerals Management Service, Pacific OCS Region, Los Angeles, California.

data for the last several years has not been processed to digital form from the analog output of the instrument (P. Komar, OSU, pers. com., 4/18/90). Similar seismometer measurements have been made at other locations along the coasts of Washington and Oregon (DOI, 1988c).

The seismometer methods were developed primarily for the purpose of providing real-time wave information near harbor entrances (DOI, 1988c).

## RECOMMENDATIONS AND CONCLUSIONS

### Recommendations

In 1988 the Minerals Management Service held a conference/workshop on recommendations for studies in Washington and Oregon (DOI 1988b). Huyer, in her conference summary of "things we don't know" about the physical oceanography of the region (DOI, 1988b, section 3.1) listed the following:

- Local intensification of alongshore flow and onshore/offshore flow - topographic influence: e.g. canyons, Hecata Bank, southern Oregon in general.
- Interannual variability.
- Structure of undercurrent (shelf break, base of slope) and variability.
- Currents offshore of shelf (both surface and deep).
- Inner shelf currents (inshore of 50 m isobath).
- Surface fronts, convergence zones.
- Bottom boundary layers.
- Structure of winds along coast.

Although many physical oceanographic characteristics of Pacific Northwest coastal waters have been studied in detail, this list provides a good summary of the areas in need of more thorough investigation. A knowledge of the physical oceanography is vital to the understanding of the interaction of the other environmental resources of the region and the movement of contaminants such as oil.

Specific studies, based on the 1988 conference recommendations, that would be of particular benefit to our understanding of the physical oceanography of the Pacific Northwest include the following:

- coastal/nearshore/estuary exchange and Columbia River plume dynamics
- fronts and Columbia River plume boundary during summer
- physical oceanography of Hecata Bank
- physical oceanography of Cape Blanco
- interannual variability study

### Conclusions

This report has summarized physical oceanography of the coast of Washington and Oregon with an emphasis on some factors considered to be most useful in describing the general physical environment.

For more detailed physical oceanographic information see the following publications: Coastal Washington - A Synthesis of Information (Strickland and Chasan, 1989); Coastal Oceanography of Washington and Oregon (Landry and Hickey, 1989); Coastal Upwelling in the California Current System (Huyer, 1983); A Summary of Knowledge of the Oregon and Washington Coastal Zone and Offshore Areas (Oceanographic Institute of Washington, 1977), and other publications.

For specific information on wave data, the Army Corps of Engineers WIS program using meteorological data and statistical hindcasting techniques (Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS), and the Minerals Management Service Coastal Wave Statistical Data Base, using high quality wave information from data buoys, (Minerals Management Service, Pacific OCS Region, Los Angeles, CA) are recommended.

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## APPENDIX A. ABBREVIATIONS AND ACRONYMS USED

| | |
|---|---|
| cm | centimeter(s) |
| cm/sec | centimeters/second |
| CWSDB | Coastal Wave Statistical Data Base |
| DOI | U.S. Department of the Interior |
| ft | feet |
| hr | hour(s) |
| in | inch(es) |
| km | kilometer(s) |
| kn | knot(s) (nautical miles per hour) |
| Lat | latitude |
| Lon | longitude |
| m | meter(s) |
| $m^3$ | cubic meters |
| MGD | million gallons per day |
| mi | statute mile(s) |
| MMS | Minerals Management Service |
| N | north |
| nm | nautical mile(s) |
| OCS | outer continental shelf |
| OSU | Oregon State University |
| $^{o}$/oo | parts per thousand |
| pers. com. | personal communication |
| POCS | Pacific Outer Continental Shelf |
| s or sec | second(s) |
| T | indicates a direction measured clockwise from true north |
| W | west |
| WIS | Wave Information Study (Corps of Engineers) |
| yr | year |

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## APPENDIX B. UNIT CONVERSION

Information for conversion between various units used in this report and other units typically used for similar applications:

length:

| | | | |
|---|---|---|---|
| 1 foot (ft) | = | 0.3048 | meter (m) |
| 1 statute miles (mi) | = | 5280. | feet (ft) |
| | = | 0.86898 | nautical mile (nm) |
| | = | 1.6093 | kilometers (km) |
| 1 nautical miles (nm) | = | 6076.11548 | feet (ft) |
| | = | 1.8520 | kilometers (km) |
| 1 inch | = | 2.54 | centimeters (cm) |

velocity:

| | | | |
|---|---|---|---|
| 1 centimeter/second (cm/s) | = | 0.01944 | knot (kn) |
| | = | 0.02237 | mile/hour (mi/hr) |
| | = | 0.03281 | foot/second (ft/sec) |
| 1 foot/second (ft/sec) | = | 0.68182 | mile/hour (mi/hr) |
| 1 knot (kn) | = | 1.15072 | mile/hour (mi/hr) |

volume:

| | | | |
|---|---|---|---|
| 1 cubic foot ($ft^3$) | = | 0.0283 | cubic meter ($m^3$) |

rate of flow:

| | | | |
|---|---|---|---|
| 1 cubic meter/sec ($m^3/s$) | = | 35.3147 | cubic feet/second ($ft^3/sec$) |
| | = | 22.8245 | million gallons per day (MGD) |
| 1 sverdrup (sv) | = | $10^6$ | cubic meters/sec ($m^3/s$) |

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## APPENDIX C. GLOSSARY AND INDEX OF TECHNICAL TERMS

For the convenience of the reader, definitions of some technical terms used in this report are given in this section. For further clarification, see the literature cited or standard textbooks on physical oceanography. Page numbers indicate pages where the terms are used.

density: pp. 17, 18, 19. Density of seawater (in SI units) is expressed in $kg/m^3$. Values in the open ocean range from about 1021 $kg/m^3$ at the surface to about 1070 $kg/m^3$ at 10,000 m depth. Density of seawater is a function of salinity, temperature, and pressure. For convenience, a quantity called $\sigma_{s,t,p}$ (sigma s, t, p), the in situ density, is defined by removing the first two digits of the density value by the equation: $\sigma_{s,t,p}$ = density-1000 (e.g. density of 1032.65 becomes 32.65). A density quantity called $\sigma_t$ (sigma t), defined by reducing the effects of pressure (on density) to surface values, is often used in applications where pressure is not a significant factor in density calculations (Pickard and Emery, 1982).

density gradient: p. 17, 19. The change of density (of seawater) per unit of distance, in the direction of maximum rate of change (or sometimes measured vertically).

ebb tide: pp. 10, 11. The flow of water out of a bay, river mouth, etc., which accompanies a falling tide (reverse is flood tide).

Ekman layer (surface): p. 18. The surface water layer less than 20 meters thick, which moves primarily in response to wind stress at the surface.

Ekman transport: p. 7. The movement of surface water resulting from the balance between frictional force of the wind and the Coriolis force due to the Earth's rotation - resulting in surface water movement to the right of wind direction in the Northern Hemisphere.

$E_{t(6)}$ and $E_{t(10)}$: p. 35. A means of expressing the energy distribution (with respect to wave period) of a wave form made up of waves having different periods. These parameters express, respectively, the percent of total energy in waves with periods of less than 6 seconds and the percent of total energy in waves with periods greater than 10 seconds.

flood tide: pp. 10, 11. The flow of water into a bay, river mouth, etc., which accompanies a rising tide (reverse is ebb tide).

halocline: pp. 13, 18. A zone of rapid change of density with depth.

hindcasting: pp. 21, 22, 26, 28, 29, 30, 32, 35, 36, 42. The calculation, from historic synoptic wind charts, of the wave characteristics that probably occurred at some past time (Hunt, 1965).

inertial current (or inertial motion): p. 10. A circular or elliptical water motion caused by the interaction of the velocity of the current, the Coriolis acceleration, and the centrifugal acceleration (latter two caused by the Earth's rotation).

isobath: p. 41. Lines of equal depth.

isopycnal: pp. 19, 20. Lines of equal density.

neap tides: p. 11. Tides during periods when the range between high and low tides is at a minimum.

nearshore: pp. 12, 23, 26, 40, 41. Within about 10 nm (18.5 km) of the coast (note that "near shore" is not the same, the range is not defined).

nutrients: pp. 7, 18. Nutrients are the substances that are needed for life. In the marine ecosystem, phytoplankton are the primary producers and as such depend on an adequate supply of light energy and a number of essential inorganic nutrients. The essential nutrients that are most in demand are inorganic carbon, inorganic combined nitrogen, inorganic phosphorus, and dissolved silicone (silicate) (Loehr, 1977).

pycnocline: pp. 17, 18, 19. A layer of maximum vertical density gradient.

recurrence interval: see return period.

return period: pp. 26, 28, 29, 30, 32, 34. The average interval of time between recurrences of waves of a given significant wave height or larger. In tables, the height of waves for fixed return periods (such as 5, 10, 50, or 100 years) are usually used. Also called recurrence interval.

significant wave height: pp. 20, 21, 28, 29, 30, 33, 34, 36. The average height of the highest one third of the waves observed.

spring tides: p. 11. Tides during periods when the height range between high and low tide is a maximum. (see neap tide.)

synoptic: p. 49. One of two major ways to approach the physical study of the oceans. The synoptic (or descriptive) approach uses observations made of specific features and reduces the description of each feature and its relationship to other features to as simple a statement as possible. The other major approach is the "dynamical" (or theoretical) approach, which applies the already known laws of physics to the oceans (Pickard and Emery, 1982).

tidal currents: pp. 10, 11, 12. Horizontal movements of water in an elliptical motion in the open ocean, in response to forces caused by the tides.

**T-S diagram**: p. 14. A graph of the temperature vs salinity taken at several depths at a station (point). A water "mass" is defined by the entire T-S curve, while a water "type" is defined by one point (i.e. a single ratio of temperature to salinity).

**upwelling**: pp. 2, 4, 7, 14, 17, 18, 19, 20, 42. Upwelling raises cold, nutrient rich waters into the photic zone along the coast, resulting in very high biomass productivity. Upwelling off Washington and Oregon is seasonal, due to seasonal variations in average wind direction. During summer, from about May to August, the surface Ekman layer (the surface water layer less than 20 meters thick, which moves primarily in response to wind stress at the surface) moves offshore because of favorable mean surface wind directions during that season (winds from the north nearly parallel to the coast), resulting in coastal upwelling within about 10-20 km (6-12 mi) of the coast.

**water mass**: pp. 1, 13, 14. Water with similar properties such as temperature and salinity at various depths, often derived from the same source or region. Water mass characteristics are modified as water is transported over long distances. Water mass characteristics are typically represented by T-S diagrams.

**wave crest**: p. 20. The highest point of a wave.

**wave height**: pp. 20, 21, 26, 27, 28, 29, 30, 31, 34, 35, 36. The vertical distance between the crest (highest point) and the next trough (lowest point) of a wave (see also significant wave height).

**wavelength**: p. 20. The horizontal distance between adjacent crests or adjacent troughs of a wave.

**wave period**: pp. 21, 26, 27, 31, 34, 35. The time interval between successive wave troughs or successive crests at a point. Related to wave frequency by the equation $\sigma = 2\pi/T$, where $\sigma$ = the angular frequency in radians per second and $T$ = the wave period in seconds.

**wave trough**: p. 20. The lowest point of a wave.

**wind stress**: pp. 10, 18, 19. The frictional force exerted by the wind on the surface of the ocean. One of the primary driving forces of ocean currents.

**zero crossing wave period**: p. 34, 35. The average time interval between similar direction crossings of mean water level for a wave record. Water level at a fixed point varies from the mean water level as a wave passes the point. Zero crossing is when water level crosses the mean water level, either in an increasing or a decreasing direction (height). Similar direction of crossing means either both increasing or both decreasing (Earle and Bishop, 1984, pp. 42 and 73).

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